EXPERIMENTAL INVESTIGATION OF COOLING
PERIMETER AND DISTURBANCE LENGTH
EFFECT ON STABILITY OF Nb₃Sn
CABLE-IN-CONDUIT CONDUCTORS

February 1992

Joseph R. ARMSTRONG
JAERI-Mレポートは、日本原子力研究所が不定期に公刊している研究報告書です。入手の際合わせ、日本原子力研究所技術情報部情報資料課（〒319-11茨城県取手市東海村）までお申し付けください。なお、このほかに財団法人原子力研究推進財団（〒319-11茨城県取手市東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly. Inquiries about availability of the reports should be addressed to Information Division, Department of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

© Japan Atomic Energy Research Institute, 1992
Experimental Investigation of Cooling Perimeter and Disturbance Length Effect on Stability of Nb$_3$Sn Cable-in-conduit Conductors

Joseph R. ARMSTRONG

Department of Fusion Engineering Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received January 24, 1992)

The stability of three coils, with similar parameters besides having differing strand diameters, was investigated experimentally using inductive heaters to input disturbances. One of the coils stability was also tested by doubling the inductive heated disturbance length to 10 cm. By computationally deriving approximate inductive heater input energy at 12 T, stability curves show fair agreement with zero-dimensional and one-dimensional computer predictions. Quench velocity and limiting currents also show good agreement with earlier work. Also, the stability measured on one of the coils below its limiting current by disturbing a 10 cm length of conductor was much less than the same samples stability using a 5 cm disturbance length.

Keywords: Cable-in-conduit Conductor, Cooling Perimeter, Disturbance Length, Nb$_3$Sn, Stability, Superconducting Magnets

* Visiting research student from Massachusetts Institute of Technology funded by US Department of Energy
3個の試験コイルの安定性に関し、誘導加熱ヒータを用いて実験的に研究した。これら3個の試験コイルは集線の直径を異にする他は同じ諸元を有するコイルである。1個の試験コイルについては誘導加熱長を2倍変化させ、安定性の破乱入熱長依存性についても調査した。誘導加熱量を知るために校正実験を行い、さらに実験条件の違いを考慮して解析にて実験値を修正し、誘導加熱量を算出した。今回の安定性実験では0次元および1次元の解析計算値と良く一致する結果を得た。常電導伝導度および制限電流値に関しても推算値と良い一致を見た。また、誘導加熱長が10cmの場合には5cmの場合と比較して安定性の顕著な低下を観測した。
Contents

1. Introduction .................................................................................. 1
2. Inductive Heater Calibrations ....................................................... 4
   2.1 Method ................................................................................... 4
      2.1.1 Power Supply .................................................................. 5
      2.1.2 Instrumentation .............................................................. 5
   2.2 Calibrations ............................................................................ 5
      2.2.1 Epoxy-resin Sample Calibration ...................................... 5
      2.2.1.1 Calculations ............................................................. 8
      2.2.2 Vacuum Calibration ....................................................... 8
      2.2.2.1 Calculations ............................................................. 11
   2.3 Discussion of Results ............................................................. 11
3. Stability Tests ............................................................................. 15
   3.1 Experimental Apparatus ......................................................... 15
      3.1.1 Sample Coils .................................................................. 15
      3.1.2 Forced Flow Helium Supply .......................................... 17
      3.1.3 Background Coils ......................................................... 17
      3.1.4 Power Supplies .............................................................. 22
      3.1.5 Instrumentation .............................................................. 22
   3.2 Sample Installation ................................................................. 22
   3.3 Experimental Procedure ......................................................... 25
      3.3.1 Cooldown ....................................................................... 25
      3.3.2 Stability Tests ............................................................... 25
4. Heating Length Dependence Test .................................................. 28
5. Results and Discussion ................................................................. 29
   5.1 Critical Current .................................................................... 29
   5.2 Stability ................................................................................. 29
   5.3 Limiting Current ................................................................... 35
   5.4 Quench Propagation Velocity ............................................... 36
   5.5 Effect of Varying Disturbance Length .................................... 37
6. Computer Modeling ..................................................................... 41
   6.1 Zero-dimensional Model ......................................................... 41
      6.1.1 Model ............................................................................ 41
      6.1.2 Results .......................................................................... 42
      6.1.3 Discussion ..................................................................... 44
目次

1. 結論 ........................................................................... 1
2. 測定加熱量の校正 ...................................................... 4
2.1 実験方法 .................................................................. 4
2.1.1 電源装置 ................................................................ 5
2.1.2 実験装置 ................................................................ 5
2.2 校正実験 .................................................................. 5
2.2.1 エポキシ含浸法による校正 ...................................... 5
2.2.1.1 計算方法 .......................................................... 8
2.2.2 真空法による校正 ................................................. 8
2.2.2.1 計算方法 .......................................................... 11
2.3 考察 ........................................................................ 11
3. 安定性実験 .............................................................. 15
3.1 実験装置 ............................................................... 15
3.1.1 試験コイル .......................................................... 15
3.1.2 強制冷媒発生装置 ................................................. 17
3.1.3 パックグラウンド磁界コイル ..................................... 17
3.1.4 電源装置 ............................................................ 22
3.1.5 計測装置 ............................................................ 22
3.2 試験コイルの準備 ..................................................... 22
3.3 実験手順 .............................................................. 25
3.3.1 初期冷凍 ........................................................... 25
3.3.2 安定性実験 ......................................................... 25
4. 加熱長依存性実験 ...................................................... 28
5. 実験結果と考察 ........................................................ 29
5.1 臨界電流値 ............................................................. 29
5.2 安定性 ................................................................. 29
5.3 制限電流値 ............................................................. 35
5.4 常電導伝播速度 ....................................................... 36
5.5 損乱入熱長の効果 ..................................................... 37
6. 数値解析 ............................................................... 41
6.1 0次元モデル .......................................................... 41
6.1.1 モデル .............................................................. 41
6.1.2 結果 ................................................................. 42
6.1.3 考察 ................................................................. 44
6.2 1次元モデル ............................................................. 44
  6.2.1 モデル ........................................................... 45
  6.2.2 結果 ................................................................. 46
     6.2.2.1 従来の熱伝達率を用いた結果 ................................. 46
     6.2.2.2 修正した熱伝達率を用いた結果 ............................. 46
  6.2.3 考察 ................................................................. 48
7. 素線径に依存する諸量の比較検討 ........................................ 49
8. 結論 ................................................................. 52
9. 提案 ................................................................. 53
    謝辞 ................................................................. 54
参考文献 ................................................................. 55
付録 ................................................................. 58
Nomenclature

\( A_{\text{cond}} \) = Area of conductor per cross section of conduit
\( A_{\text{cs}} \) = Total area inside conduit inner diameter
\( A_{\text{cu}} \) = Area of pure copper after heat treatment, measured by magneto-resistance
\( A_{\text{he}} \) = Area of helium space per cross section of conduit
\( B \) = Magnetic flux density
\( C \) = Equation constant
\( C_p \) = Specific heat of conductor
\( C_{\text{pe}} \) = Specific heat of epoxy-resin
\( C_{\text{pf}} \) = Specific heat of helium
\( D_h \) = Hydraulic diameter of the conduit considering only the strands' perimeter, defined as \( \frac{4 A_{\text{he}}}{P_c} \)
\( D_{\text{hc}} \) = Hydraulic diameter of the conduit considering both the strands' perimeter and the conduit's inner perimeter, defined as \( \frac{4 A_{\text{he}}}{P_c + P_{\text{cond in}}} \)
\( d_{\text{st}} \) = Diameter of strand
\( \delta \) = Skin depth of inductive heating
\( E_{\text{in}} \) = Input energy to the conductor
\( \eta \) = Efficiency of cryogenic pump
\( F \) = Function used in the inductive heating energy equation and is a function of \( \frac{d_{\text{st}}}{\delta} \)
\( F_f \) = Friction of fluid
\( f \) = Factor of amount of electrical energy used at room temperature per energy input to the liquid helium
\( f_{\text{cond}} \) = Fraction of conductor per cross section of conduit
\( f_{\text{cu}} \) = Fraction of copper in the conductor strands
\( f_D \) = Darcy's friction factor
\( f_{\text{he}} \) = Fraction of helium heat capacity which is effectively used to cool the conductor
\( f_{\text{Pc}} \) = Fraction of total cooling perimeter which is utilized to cool the conductor.
\( g \) = Acceleration of gravity
\( \gamma_{\text{cu}} \) = Density of copper
\( \gamma_{\text{ep}} \) = Density of epoxy resin
\( \gamma_{\text{he}} \) = Density of helium
\( h \) = Heat transfer coefficient
\( h_k \) = Kapitza heat transfer coefficient
\( h_s \) = Steady state heat transfer coefficient

(7)
\( h_t \) = Transient heat transfer coefficient
\( I \) = Transport current to sample
\( I_{IH} \) = Current supplied to inductive heaters
\( I_{lim} \) = Limiting current of sample
\( j \) = Current density per strand area
\( j_{c} \) = Critical current density per strand area
\( j_{cu} \) = Current density per copper area
\( j_{lim} \) = Limiting current's current density per cable space
\( k \) = Variable used in Dresner's limiting current equation
\( L_{\text{cond}} \) = Total length of conductor
\( L_h \) = Length of input disturbance zone
\( \lambda \) = Thermal conductivity of helium
\( \lambda_{\text{cond}} \) = Thermal conductivity of conductor
\( \dot{m} \) = Mass flow rate of supercritical helium
\( \mu \) = Magnetic permeability
\( \mu_{\text{vis}} \) = Viscosity of helium
\( n \) = Exponential factor for critical current equation
\( \omega \) = Inductive heater signal frequency
\( P \) = Pressure of forced-flow helium
\( P_c \) = Cooling perimeter considering all of the sample's strands
\( P_{\text{cond in}} \) = Inside perimeter of the conduit
\( P_{\text{in}} \) = Inlet pressure of helium
\( \phi \) = Potential function

\( Pr \) = Prandtl number of helium \( \left( Pr = \frac{C_p f \mu_{\text{vis}}}{\lambda} \right) \)
\( Q_{\text{he}} \) = Heat transfer rate to helium from conductor
\( Q_{\text{ex}} \) = Heat transfer rate to conductor from external disturbance
\( Q_j \) = Heating rate from to conductor from Joule heating
\( Re \) = Reynolds number of helium \( \left( Re = \frac{\gamma_{\text{he}} v D_h}{\mu_{\text{vis}}} \right) \)
\( \rho \) = Electrical resistivity
\( t \) = Time
\( T_c \) = Critical temperature of conductor
\( T_{\text{cond}} \) = Temperature of conductor
\( T_{cs} \) = Current sharing temperature of the sample
\( T_{\text{he}} \) = Temperature of forced-flow helium
\( T_{\text{sam}} \) = Temperature of epoxy-resin impregnated inductive heater calibration sample
\( t_q \) = Time after initiation of quench
\( \tau_h \) = Inductive heater pulse duration
\( U \) = Internal energy
\( v \) = Velocity of helium
\( V \) = Velocity of propagating normal zone
\( W_{pa} \) = Actual energy supplied by pump to liquid helium
\( W_{pe} \) = Electrical energy supplied to the cryogenic pump
\( x \) = Longitudinal length along the conductor
1. Introduction

Two of the most popular forms of energy production for commercial use today are oil burning and nuclear fission energy. The two methods, however, have many problems. As far as oil burning, we have already used up over an estimated half of this earth's resource in the current century, and the burning creates many harmful gases which are causing negative effects on the environment [1]. Nuclear fission has been the latest advance in energy production, but the by-products of such a reaction are hazardous, and the reaction can accidently continue uncontrollably producing deadly results.

One of the most promising alternative energy sources seems to be nuclear fusion. Fusion energy involves combining two hydrogen atoms to produce a helium atom and excess energy. The conditions for such a reaction to occur, however, are difficult to obtain. The goal is to try to achieve a high temperature and high density plasma. In order to confine this material, two methods are being heavily investigated, laser and magnetic confinement [1,2,3].

Magnetic confinement now seems to produce the best results [4]. Currently, one of the most advanced tokamak plasma confinement devices is operated at the Japan Atomic Energy Research Institute, the JT-60 [2]. This tokamak uses water cooled resistive magnets to produce its high magnetic field. However, this type of field production produces an enormous amount of wasted heat energy caused by resistive heating, which would probably be greater than the energy produced by the reactor [4]. For the next generation fusion machines, such as the International Thermonuclear Experimental Reactor (ITER), superconducting magnets are needed to achieve the specified magnetic fields without consuming enormous amounts of energy.

Superconducting magnets have operated successfully for many years in different applications. Most of these magnets are pool-cooled (placed in a pool of liquid helium). This type of cooling is insufficient for fusion reactors because of the high strength and large quench dump voltages required. Now, cable-in-conduit conductors are being developed for this application [5]. These conductors are cooled by forcing helium through a conduit in which the superconducting wires are also wound.
The stability of such conductors is a major problem for designers. A small disturbance, caused by such things as a strand movement or AC losses, can cause the entire length of the conductor to transfer to normal resistivity. The goal of designers is to create a stable magnet that will handle high currents [6].

The designer has many variables which to work with when designing the cable-in-conduit conductor (CICC), including materials, copper ratios, void fractions, flow conditions, strand coating, AC loss characteristics, and strand diameter [5]. The purpose of this paper is to study the effect of strand diameter on stability. Earlier work by Agatsuma has predicted stability numerically as a function of cooling perimeter (and therefore strand diameter), but he did not confirm these results experimentally [7,8].

Work was undertaken at JAERI to test three coils of similar parameters except for strand diameters (see table 1 for specifications). Total cross sectional area of the strands in the conduit was kept constant by varying the number of strands between the samples. This allowed the void fraction (defined as helium space/conduit cross section space) to be approximately the same for all three samples. These results were also attempted to be modeled using computer simulations (both zero-dimensional and one-dimensional predictions).

Tests were also performed to compare the stability when the disturbance length was varied. It was found that a 10 cm disturbance length was on the order of half as stable as a 5 cm disturbance length. This is contradictory to earlier results by Wong [6]. However, this difference can be explained by the different test conditions. These results are also discussed.
Table 1: Conductor specifications of sample coils

<table>
<thead>
<tr>
<th>Strands</th>
<th>Test Sample A</th>
<th>Test Sample B</th>
<th>Test Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Stands</td>
<td>27</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>Diameter</td>
<td>1.06 mm</td>
<td>1.31 mm</td>
<td>1.59 mm</td>
</tr>
<tr>
<td>Diameter of Insulated Coated</td>
<td>1.07 mm</td>
<td>1.32 mm</td>
<td>1.60 mm</td>
</tr>
<tr>
<td>Cooling Perimeter</td>
<td>90.8 mm</td>
<td>74.6 mm</td>
<td>60.3 mm</td>
</tr>
<tr>
<td>Insulation Thickness of Insulation</td>
<td>Chrome Plating</td>
<td>Chrome Plating</td>
<td>Chrome Plating</td>
</tr>
<tr>
<td>Copper Ratio of Strand (Cu/Non-Cu)</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Twist Pitch</td>
<td>32 mm</td>
<td>40 mm</td>
<td>49 mm</td>
</tr>
<tr>
<td>Number of Filaments per Strand</td>
<td>108</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>Filaments Diameter of Filaments</td>
<td>0.060 mm</td>
<td>0.074 mm</td>
<td>0.090 mm</td>
</tr>
<tr>
<td>Material</td>
<td>Nb₃Sn</td>
<td>Nb₃Sn</td>
<td>Nb₃Sn</td>
</tr>
<tr>
<td>Conduit Sheet and Conduit Material</td>
<td>SS304</td>
<td>SS 304</td>
<td>SS 304</td>
</tr>
<tr>
<td>Inner Diameter of Conduit</td>
<td>7.34 mm</td>
<td>7.34 mm</td>
<td>7.34 mm</td>
</tr>
<tr>
<td>Outer Diameter of Conduit</td>
<td>9.50 mm</td>
<td>9.50 mm</td>
<td>9.50 mm</td>
</tr>
<tr>
<td>Sheet Winding Method</td>
<td>half wrap winding</td>
<td>half wrap winding</td>
<td>half wrap winding</td>
</tr>
<tr>
<td>Sheet Thickness</td>
<td>0.025 mm</td>
<td>0.025 mm</td>
<td>0.025 mm</td>
</tr>
<tr>
<td>Ratio of Space (Helium Space/Overall Area)</td>
<td>39.9%</td>
<td>39.1%</td>
<td>40.0%</td>
</tr>
</tbody>
</table>
2. Inductive Heater Calibrations

Stability of superconductors is measured by inputting a disturbance into a conductor and monitoring whether the conductor quenches or recovers. For the experiments presented, in order to input a disturbance, inductive heaters were used. Inductive heaters have the advantage as to not interfere with the cable space, to input the energy uniformly, and to enable heating of the strands without a time lag, three common problems with resistive heaters. Inductive heaters, however, have a problem of accurate judging of the input energy [9].

Calculations have been inadequate to predict this input energy. According to calculations [10]

\[ E_{in} \propto \sum I_{IH}^2 \]

However, averaging the data taken from seven previous DPC calibrations [11] shows that

\[ E \propto \left( \sum I_{IH}^2 \right)^{1.2} \]

The problem with the predictions seems to be that the predictions are for homogeneous round cross-sections, while the sample is actually made of a number of strands which are composed of copper, insulator, and superconductor.

2.1 Method

Because of these problems, it becomes necessary to calibrate the inductive heaters experimentally. These experiments involved using a short section of conductor which was inductively heated. The maximum temperature of the sample at the end of this inductive heat pulse was measure by using thermocouples. Then, this temperature rise was used to calculate the input energy as a function of the input signal to the inductive heater.
2.1.1 Power Supply

For the calibration and stability experiment, a 600 V - 1000 A power supply was used to input the disturbance energy. The circuit is set up to produce an AC waveform of desired length and power (see figure 1 for diagram of power supply).

For all of the tests, a 1 kHz - 3 ms inductive heater pulse was chosen. A diagram of the typical pulse can be seen in the figure 2. Initially, a 10 ms pulse was chosen, but this proved to be too large of an energy input. Therefore, at the beginning of sample A's test, the pulse width was switched to 3 ms.

2.1.2 Instrumentation

The input energy created a temperature rise of the sample which was measured using "normal silver" Au 0.07% Fe thermocouples. These signals were recorded using both a digital memory and X-T recorders. The digital memory was also used to analyze the inductive heater's input waveform for calculations of average current and the integral of current squared versus time.

For the vacuum inductive heater calibration test, it was also necessary to measure the temperature of the thermocouples base point since this point was inside the vacuum. This was done by using a germanium resistance thermometer with a 10 μA input. This voltage signal was recorded on the X-T recorder. Using this reading and the thermocouples' reading, an accurate temperature of the sample before the disturbance was input could be determined.

2.2 Calibrations

Two calibration methods were performed; a epoxy-resin impregnated technique and a vacuum technique.

2.2.1 Epoxy-resin Sample Calibration

An epoxy-resin impregnated inductive heater calibration sample was produced. This calibration sample (as seen in figure 3 and photo 1) has a short length of CICC impregnated and surrounded by epoxy-resin. The calibration samples were equipped with inductive heaters, which had the same dimensions as the stability sample coils' heaters, at the center of their lengths.
Figure 1: Diagram of inductive heater power supply [12]

Note: Diagram used with permission of author

Figure 2: Example of waveform supplied to inductive heaters
Inductive Heater Calibration Sample

Figure 3: Sketch of epoxy-impregnated inductive heater calibration sample

Photo 1: Epoxy-impregnated inductive heater calibration sample.
The calibration sample also had thermocouples at four locations installed by drilling 1 mm diameter holes in the sample. The two center-bore sample thermocouples on all three samples were electrically shorted to one another, and therefore made contact with the strands.

This sample was installed in a holder and submerged in liquid helium, which also submerged the thermocouple junction point (figure 4 and photo 2). The sample was heated by its inductive heater and temperature rise was measured. After waiting for the sample to cool to 4.2 K, this technique was repeated approximately 20 times at varying heating energies.

2.2.1.1 Calculations

During this experiment, the temperature rise was recorded by the digital memory. The peak temperature rise, which occurred shortly after the pulse, was then used to calculate energy input per volume by

\[
E_{\text{in}} \left[ \frac{\text{mJ}}{\text{cm}^3 \text{ vol}} \right] = \left( \frac{A_{\text{he}}}{A_{\text{cs}}} \right) \gamma_e \int_{T=4.2 \text{ K}}^{T_{\text{peak}}} C_p \, dT_{\text{sam}} + \left( \frac{A_{\text{cond}}}{A_{\text{cs}}} \right) \gamma_{\text{cu}} \int_{4.2 \text{ K}}^{T_{\text{peak}}} C_p \, dT_{\text{sam}}.
\]

This result was then multiplied by the volume of the sample (defined as cross sectional area times sample length) and divided by the heated volume (defined as strand cross sectional area times heated length) to get the results in mJ/cm³ strand (see figure 5).

2.2.2 Vacuum Calibration

A second calibration was done after the stability tests using a vacuum technique. The samples of this test were not epoxy-resin impregnated and were tested in a vacuum; therefore, the uncertainty caused by heat dissipation to the epoxy-resin was eliminated. Because this method was done with an inductive heated wrapped on the vacuum tube instead of on the sample, results were converted to stability test samples' inductive heater signal inputs by calculating equivalent magnetic flux of the heaters.

A 5 cm length of each previously tested sample coil was removed and cleaned. Two thermocouples were then attached to either longitudinal side of the sample directly to a different single strand near the center of the sample. This sample was then placed
Inductive Heater Calibration Setup

Figure 4: Sketch of setup for epoxy-impregnated method inductive heater calibrations

Photo 2: Epoxy-impregnated inductive heater calibration sample installed in holder.
Figure 5: Calibration curve for energy input into conductor from inductive heater pulse. This curve is derived from epoxy-impregnated method sample calibration.
inside a tube which had an inductive heater wrapped on its outer
diameter (see figure 6). The inside of the tube was made a vacuum,
and then the assembly was placed inside a liquid helium cryostat.
The same procedure as in the epoxy-resin calibration was then
followed by pulsing the heater and measuring the maximum
temperature rise.

2.2.2.1 Calculations

The two thermocouples time verse voltage waveforms were
compared, and the thermocouple's data which had the sharper
voltage rise was used for the calculations. (For sample A and B,
each sample's two thermocouples' waveforms were identical, while
sample C had slightly different waveforms. This difference was
probably caused by a poor solder connection.)

The initial temperature of the sample (varied from 4.12 to
4.37) was measured by using a germanium resistance thermometer
embedded in a copper block at the bottom of the vacuum tube.
This block was also used as the junction point for the
thermocouples; therefore, the voltage of the thermocouples could be
used to determine the initial sample temperature.

The equation

$$E_{\text{in}} \left[ \frac{\text{mJ}}{\text{cm}^3 \text{ strand}} \right] = \gamma_{\text{cu}} \frac{T_{\text{peak}}}{\int C_p \ dT_{\text{cond}}}
\text{ at } T_{\text{initial}}$$

was then used to calculate the input energy for a given heater pulse
(see figure 7 for calibration curves).

2.3 Discussion of Results

The data was graphed and fitted to the curve;

$$E_{\text{in}} = C_1 \left( \sum I^2 \right) C_2$$

with $C_1$ and $C_2$ being factors determined by best fit lines. For the
epoxy-resin sample (as seen in figure 5), the $C_2$ factors varied as
1.15, 1.39, and 1.37, while for the vacuum calibration, these factors
varied as 1.09, 1.10, 1.09. According to theory of a solid cylinder
Figure 6: Sketch of setup for vacuum method inductive heater calibration
Figure 7: Calibration curve for energy input into conductor from inductive heater pulse. This curve is derived for the vacuum method sample calibration.
with no superconductor, this factor should be equal to 1. Because of the similarity in the vacuum calibration samples' $C_2$ factors, this calibration data was used for the stability comparisons.

For the epoxy-resin impregnated method, the discrepancy in factors is theorized to be caused by the difference in heat transfer rate in the strands and in the epoxy-resin. After the input pulse, heat transfer continues from the strands to the epoxy-resin. Therefore, the maximum temperature recorded is probably not the equilibrium temperature which is assumed in the analysis.

As discussed in the results section, the vacuum method results, which were calibrated with no background magnetic field, were then used to derive calibration curves at 12 T.
3. Stability Tests

A series of experiments was performed to measure the stability margin of the three sample coils. Stability tests, performed at conditions defined in table 2, were done by inductively imputing

Table 2: Test conditions for stability tests.
*Where noted, this length was changed to 10 cm.

<table>
<thead>
<tr>
<th>Background Field</th>
<th>B</th>
<th>= 12 Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forced Flow Helium</td>
<td>T₀</td>
<td>= 4.2 K</td>
</tr>
<tr>
<td></td>
<td>Pᵢₑᵣ</td>
<td>= 6 atm</td>
</tr>
<tr>
<td></td>
<td>m</td>
<td>= 0.8 g/s</td>
</tr>
<tr>
<td>Inductive Heater</td>
<td>τ</td>
<td>= 3 ms pulse</td>
</tr>
<tr>
<td>Input Energy</td>
<td>ω</td>
<td>= 2π kilo-rad/s</td>
</tr>
<tr>
<td></td>
<td>L_h</td>
<td>= 5 cm *</td>
</tr>
</tbody>
</table>

disturbances to create a short normal zone in the conductor and monitoring whether this caused the sample coil to quenched or recovered (see figure 8 for simplified diagram of setup). The stability margin is defined as the largest input energy per unit volume for given conditions for which the conductor will recover to superconducting state [13].

3.1 Experimental Apparatus

3.1.1 Sample Coils

Three sample coils were tested. These sample conductors had similar properties (such as void fraction, overall strand cross sectional area, copper ratio, etc), but varied by the diameter of the conductor (refer again to table 1). The number of strands was also varied to approximate the same overall cross sectional area of the conductors. This resulted in a varying cooling perimeter from 6 to 9 cm between the coils.
Figure 8: Simplified diagram of experimental setup.
The manufacturing of three samples was identical other than the diameter of the strands. All the strands were manufactured from the same parameter billets, and therefore have the same number of filaments and the same copper ratio. The diameter was determined by the final die in the drawing process (figure 9). The Nb$_3$Sn tube-processed conductor was then heat treated for 20 hours after winding.

The conductors were wound into sample coils, as can be seen in figure 10 and photos 3. The sample coils consisted of approximately 11 turns which were supported and insulated by epoxy-resin. The conductor terminated in "helium boxes" where the joint from normal conductor to superconductor was made. This configuration has a total superconductor length of 7.15 meters.

3.1.2 Forced Flow Helium Supply

Supercritical helium was used for the experiments. This helium was supplied with the following properties;

\[
T_{in} = 4.2 \text{ K} \\
P_{in} = 6.0 \text{ atm} \\
\dot{m} = 0.8 \text{ g/s}.
\]

A diagram of the supply system can be seen in figure 11. The gaseous helium was precooled in LN$_2$, and pumped through a series of heat exchangers which cooled the helium to liquid state before reaching the coil. After the helium entered the sample’s cryostat, the helium was again cooled by the 4.2 K bath to remove the heat that might have entered during the transfer from the helium supply dewar to the sample’s cryostat.

3.1.3 Background Coils

JAERI’s 13 T large bore superconducting magnet was used to produce the background field for the tests. This magnet consists of two windings; the outer layer is NbTi and the inner is Nb$_3$Sn [14]. For these experiments, the magnet was only brought to a current to produce 12 T (1224 A).
Manufacturing Process of Strand

Figure 9: Manufacturing process of strands.
Figure 10: Diagram of sample coils
Photo 3: Sample coils before test preparation.
Figure 11: Diagram of supercritical helium supply
3.1.4 Power Supplies

Three power supplies were used for the experiment: the background magnet's, the sample's, and the inductive heater's power supplies.

The background magnet monitoring was controlled by automatic circuitry which dumped the current as quickly as possible after a large disturbance in this magnet was detected [14] (see figure 12).

The samples power supply ramped up to the test current at 1 kA/min and then held at this steady state current. The rapid discharge (ramp down) of the current after quench was controlled manually in order to allow time for the quench to propagate for quench propagation measurements (see figure 13).

The inductive heater power supply, described earlier in the inductive heater section, output signal's voltage peak current was varied to control the input disturbance energy to the sample.

3.1.5 Instrumentation

During the stability tests, the sample coil's voltage at each turn, inlet and outlet pressures, and mass flow rate was monitored (see figure 14 for diagram of instrumentation locations). These signals were first amplified by isolation amplifiers and then sent in parallel to X-T recorders and a digital memory. For measurement of critical current, the voltage over the center turn was also monitored versus coil transport current using a X-Y recorder.

Inductive heater pulse signals were monitored using a separate digital memory/signal analyzer. This pulse signal was also used as the trigger for data collection of the coil.

3.2 Sample Installation

Samples were received from the manufacturer as shown in photo 3. After receiving the coils, the wiring was connected and the conductor which would be subject to large Lorentz forces was supported.
Figure 12: Background coils' electrical circuit

Figure 13: Sample coils' electrical circuit
Figure 14: Diagram of instrumentation signal locations on sample coils.

V = Coil Voltage Tap
VL = Lead Voltage Tap
P = Pressure Tap
\( \dot{m}_{he} \) = Mass Flow Rate Meter
IH = Inductive Heaters
PS = Power Supply
Before inserting into the background magnet, two verification tests were done. First, a leak test of the piping for the forced-flow system was performed at 10 kg cm\(^{-2}\). Then, it was verified that the coil, inductive heaters, the background coil, and ground were electrically insulated. The sample was then positioned in its support such that the center turn of the sample was at the center of the background field. (see figure 15 and photo 4).

3.3 Experimental Procedure

3.3.1 Cooldown

The conduit was first flushed of air by flowing gaseous helium. During the cooldown from room temperature to 4.2 K, a low flow rate of GHe cooled by LN\(_2\) was flowed through the conduit. Once LHe transfer to the background magnet was well under way, the flow of super-critical helium (SHe) was started in the conduit.

The cryostat, in which the sample coil and the background magnet were installed, was first filled with LN\(_2\). After filling, this LN\(_2\) was boiled off to the outer 77 K shield and replaced by GN\(_2\). After completely flushing the magnet vessel of LN\(_2\), the vessel was vacuum pumped to approximately -0.8 kg/cm\(^2\) and refilled with GHe three times to replace the N\(_2\) with He. Next, a small flow of GN was supplied to the 77K shield in order to prevent possible freezing of inlet and outlet valves. LHe transfer was then started and continued until the magnets were submerged.

During the entire cooldown phase, a small current (5 to 10 A) was circulated in the sample coil and the sample turn voltages were recorded using X-T recorders. These reading gave accurate measurements of the superconducting transition resistivity.

3.3.2 Stability Tests

First, the background magnet and sample coil dump time constants and instrumentation were checked. It was also determined that the sample could be discharged at 50 kA/min without causing too high an induced voltage on the background coil. Then, after ramping up the background coil to 12 T, the sample coil was ramped up to its test current at 1 kA/min. After achieving test
Figure 15: Sketch of sample installed in background coil.

Photo 4: Sample coil installed in background coil.
current, the sample was held for approximately 5 minutes to assure steady state.

Critical current was measured at 12 T by ramping up the current at 1.0 and, at higher currents, 0.5 kA/min. The voltage versus transport current over the center turn of the sample was monitored using a X-Y recorder. When the voltage reached about 25 µV, the sample was ramped down to prevent a high current quench which could lead to the quench of the background field magnet.

Stability tests were then begun by activating the inductive heater at low energies at first in order to define recovery energies. The input energy was increased in steps until the sample quenched.

This process was repeated at several transport currents. Especially for sample B and C, which have distinct limiting currents, in order to better define their limiting currents, transport currents around this limiting currents were tested.

Transport currents were varied until a stability trace of the coils could be determined at the test conditions (5 cm disturbance length, 3 ms pulse, 4.2 K and 6 atm helium, and 0.8 m/s flow rate).
4. Heating Length Dependence Test

For the stability comparison tests, a 5 cm length inductive heater was used to input the energy disturbance. Does this input energy situation simulate a long length disturbance, which could be caused by plasma disruption, or a point disturbance, which could be caused by a localized conductor motion? To investigate this question, during the test of sample C, stability in the well-cooled region was also measured using a 10 cm heated length.

The sample was equipped at center turn of its solenoid with four 5 cm inductive heaters which were positioned adjacent to each other (see photo 5). Using two adjacent heaters connected in series (all four inductive heaters could not be used because one was shorted to the coil), which produced a 10 cm disturbance length, a stability test of sample C at three currents below its limiting current was performed. The same method of determining the stability margin as mentioned in the previous section was followed.

Photo 5: Inductive heaters installed on center turn. Photograph taken before sample surrounded with epoxy.
5. Results and Discussion

5.1 Critical Current

Using the experimental traces of the samples' center turn voltage verse transport current, the relationship [4]

\[
\left( \frac{\rho}{\rho_0} \right) = \left( \frac{j}{j_0} \right)^n
\]

(with \( \rho_0 \) and \( j_0 \) measured resistivity and current density) was used to extrapolate the resistance at currents higher than experimentally measured. Using this equation, the \( n \) values for samples A, B, and C are 27, 20, and 21, respectively.

The critical current at 12 T of the three samples, using the definition of \( \rho = 10^{-13} \Omega \cdot m \), varied as follows;

Sample A's Critical Current = 6222 A \( \left( j_{c\ 12T} = 2.56 \times 10^8 \frac{A}{m^2} \right) \)

Sample B's Critical Current = 5676 A \( \left( j_{c\ 12T} = 2.30 \times 10^8 \frac{A}{m^2} \right) \)

Sample C's Critical Current = 5488 A \( \left( j_{c\ 12T} = 2.27 \times 10^8 \frac{A}{m^2} \right) \).

(Note the \( j_c \) is calculated as critical current per strand area.) Using critical current as the criteria, note that the 20 hr heat-treatment is best for sample A as compared with the larger diameter/thicker filament strands of sample B and sample C.

5.2 Stability

As stated earlier, the vacuum-method inductive heater calibration relation was used, which has exponents which are in good agreement with earlier inductive heater calibrations performed at JAERI, to relate inductive heater input signals to sample input disturbance energy. Figure 16 shows the stability when using this calibration.
Figure 16: Stability curves using vacuum method inductive heater calibrations.
Calibration at 0 T is the method used in many of the inductive heater experiments referenced \([9,12,15]\). However, in order to determine the input energy for the stability test performed at 12 T, data of the calibration test carried out at 0 T should be modified. According to the inductive input energy relationship

\[
E_{in} = \frac{\omega B_{peak}^2}{2\mu} \left(\frac{d_{st}}{\delta}\right)^F
\]

(with \(F\) a function which increases below \(\frac{d_{st}}{\delta} = 3.5\) and then decreases for higher values) is a function of skin depth \([10]\). Skin depth is defined by

\[
\delta = \sqrt{\frac{2\rho}{\mu \omega}}.
\]

Therefore, input energy is a function of resistivity, which depends upon the background magnetic field.

The vacuum-method calibration curves equations for no background field are:

- **Sample A:** 
  \[E_{in} = 2.8 \times 10^{-3} \left(\sum I_{jH}^2\right)^{1.1}\]

- **Sample B:** 
  \[E_{in} = 1.9 \times 10^{-3} \left(\sum I_{jH}^2\right)^{1.1}\]

- **Sample C:** 
  \[E_{in} = 1.5 \times 10^{-3} \left(\sum I_{jH}^2\right)^{1.1}\]

The input energy \(F\) functions for each sample at 0 T superconducting transition resistivities are; sample A's \(F = 0.27\), sample B's \(F = 0.20\), and sample C's \(F = 0.14\). Assuming the longitudinal and circumferential resistivities are the same (because the samples are Nb_3Sn and wound before reaction), these factors have good relation with the test data.

Using this relation between calculation and experimental data, the \(F\)'s at 12 T were used to calculate new calibration curves. To calculate the \(F\)'s, however, the resistivities at 12 T were needed. The 12 T resistivities,
Sample A's 12 T $\rho_{\text{cu}} = 6.34 \times 10^{-10}$ $\Omega\cdot\text{m}$
Sample B's 12 T $\rho_{\text{cu}} = 5.99 \times 10^{-10}$ $\Omega\cdot\text{m}$
Sample C's 12 T $\rho_{\text{cu}} = 5.32 \times 10^{-10}$ $\Omega\cdot\text{m}$,

were determined from voltage traces during coil quenches. The distance between the center voltage taps was 0.63 m, allowing time for the center of the normal zone to heat and therefore increase in resistance. Because of this, only low current (and therefore low Joule heating) quenches were analyzed. Immediately after the section reached full normal, the slope of the trace was used to estimate to voltage with the entire length at SC transition temperature.

Using this data, the 0 T calibration curves were multiplied by $\frac{F_{12\text{T}}}{F_0\text{T}}$ (the F's calculated at the different resistivities) in order to determine 12 T inductive heater calibration curves (see figure 17). Note that the calibration lines are approximately equal. Allowing for error in resistivity and temperature measurements, it was decided to create one calibration curve for all the three samples (see figure 18). This 12 T calibration line relating input signal to the inductive heater to input disturbance energy to the conductor is

$$E_{\text{in}} = 3.7 \times 10^{-3} \left( \sum I_{\text{IH}}^2 \right)^{1.1}$$

The stability plot using this 12 T approximate calibration curve can be seen in figure 19. Compared with sample A's stability, sample B's and sample C's stabilities at the same transport current (note that the graph uses normalized transport current), are roughly 75% and 40% in the well-cooled region and about equal above the limiting current.

Note that these results use calculated approximations for the 12 T calibration curves. Later experiments are planned at JAERI to investigate the question of variation of input energy as a function of background field. With the results of this experiment, the accuracy of these approximations will be checked and presented in a later report.
Figure 17: Calculated 12 T inductive heater energy input curves based on vacuum method inductive heater calibration curves.

Figure 18: Averaged calculated 12 T inductive heater energy input curves based on vacuum method inductive heater calibration curves.
Figure 19: Stability curves based on averaged calculated 12 T inductive heater energy input curves.
5.3 Limiting Current

Coil B and C showed definite limiting currents while coil A's was harder to determine. Two methods were used to predict the limiting currents. Stekly's formula,

\[ I_{\text{lim}} = \sqrt{\frac{h \left( T_c - T_o \right) A_{\text{cu}} P_c}{\rho_{12T}}} \]

was used with \( h = 1000 \frac{W}{m^2 \cdot K} \), similar to earlier work [16,17,18]. Dresner's limiting current equation [19], with modifications by Miller and Lue [20], is

\[ I_{\text{lim}} \propto \sqrt{\frac{A_{\text{cu}} A_{\text{he}}}{A_{\text{cu}}} \left( \frac{T_c - T_o}{\rho_{\text{cu}}} \right)^{1/2} \left( \frac{L_h}{D_h t_h} \right)^{1/15}} \]

Note that Dresner's equation is a proportionality, and therefore one limiting current must be used as a base to determine the others. A modification to this equation, proposed by Miller which eliminates the proportion [21], is

\[ j_{\text{lim}} = k \left[ f_{\text{cu}} f_{\text{cond}} (1 - f_{\text{cond}}) \right]^{1/2} \left( \frac{T_c - T_o}{\rho_{\text{cu}}} \right)^{1/2} L_h^{2/15} \frac{1/2}{D_h^{1/2}} \frac{1/15}{D_h^{1/2}} \frac{1/2}{D_h^{1/2}} \]

Calculations were performed using a \( k \) value experimentally found by Miller to be \( \approx 0.9 \) at pressure of 6 atm.

Table 3: Comparison of experimental limiting currents to predictions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Experimental Results</th>
<th>Stekly's Equation</th>
<th>Dresner's Proportional Equation</th>
<th>Dresner's k factor Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>(3333 to 4167 A)</td>
<td>3294 A</td>
<td>3841 A</td>
<td>2280 A</td>
</tr>
<tr>
<td>Sample B</td>
<td>( \approx 3300 ) A</td>
<td>3129 A</td>
<td>{base 3300 A}</td>
<td>2117 A</td>
</tr>
<tr>
<td>Sample C</td>
<td>( \approx 2900 ) A</td>
<td>2986 A</td>
<td>2810 A</td>
<td>1809 A</td>
</tr>
</tbody>
</table>
The results of these calculations are summarized in table 3. Note that the limiting current for sample A is hard to determine from the stability results. However, from quench data at transport currents of 3333 A and 4167 A, the limiting current seems to lie between these two currents. At 3333 A, the conductor shows a partial recovery before growth of the normal zone, while at 4167 A the normal zone continues to grow immediately after the pulse. Also note that for Dresner's proportional equation, sample B's experimental limiting current is taken as a base for prediction of the other limiting currents.

Of the three predictions, the best results are obtained by Dresner's proportional equation. When comparing the percentage differences of the predictions to the experimental results, this equation predicts the differences well. From these experimental results, it can be confirmed that

\[ I_{\text{lim}} \propto P_c \]

as concluded by Dresner [19] and earlier presented by Phelan [18].

5.4 Quench Propagation Velocity

Quench velocity was measured using the voltage taps positioned along the length of the coil. From data on the sample current, the time was recorded before the sample current was decreased. For times below this ramp-down time, the time each turn went full normal was recorded and used to calculate propagation velocities.

Earlier work by Ando [17] and Dresner [22] predicted that quench velocity grows with time. Ando's relationship states that

\[ V \propto I^{2.8} t_q^{0.6}. \]

The experimental results for the three coils show that propagation velocity is not effected by cooling perimeter. Graphs of quench velocity versus time and versus transport current shows that the quench velocity of all three coils grew on the average as the proportion

\[ V \propto I^{3.3} t_q^{0.8}. \]
Because of the relatively low amount of data collected before current ramp down, this relationship agrees well with Ando's conclusions.

5.5 Effect of Varying Disturbance Length

During the test of sample C, the stability was also checked at currents below its limiting current for a 10 cm disturbance length (see figure 20 for stability plot). This result shows that stability decreases with the increasing disturbance length.

Experimental results contradicted earlier conclusions by Wong [6]. He ran simulations on a 20 cm and 40 cm disturbance length on the large coil US-DPC. He concluded that the 40 cm induced a higher flow causing better heat transfer and higher stability. In his model, for a 10 ms pulse, the helium only travels 4 cm, and therefore this difference in heated zones only increases the helium temperature slightly.

Figure 21 shows quench voltage profiles for V_{6.7} (the voltage over the center turn) for three currents below it limiting current for the 5 cm and 10 cm cases. These quench profiles are from the close to stability margin quenches. Note that the scales are identical for each trace. Initially, during heat input, the voltage of the 10 cm cases are greater, signifying that more of the conductor is normal. After the pulse, both normal zones shrink, producing lower voltages. After this partial recovery, both cases start their growth to full normal.

The sample coils have a relatively high copper ratio (design ratio = 1.9). Therefore, when the coil becomes normal, the current density in the copper is low which produces low Joule heating. This Joule heating induces less of a flow. Assuming this induced flow is half of Wong's prediction [6], this estimates the helium to have traveled 2 cm in the 10 ms after initiation of pulse. This length is a significant portion of the 5 cm heated length as compared with the 10 cm heated length. For the 5 cm case, a greater proportion of the initially highly heated (because of Kapitza heat transfer) helium is flushed from the heated zone, causing a higher stability even though induced flow is greater for the 10 cm case.
Figure 20: Stability curves of sample C for input energy disturbance lengths of 5 and 10 cm based on averaged calculated 12 T inductive heater energy input curves.
Figure 21: Voltage vs time traces from center turn of sample C for 5 and 10 cm disturbance lengths at three currents below the sample's limiting current.
This higher stability was confirmed computationally. One-dimensional computer analysis on the test coils shows the 5 cm heated lengths to be more stable than the 10 cm lengths.

The difference with Wong's predictions seem to be caused by the size of the induced flow and the size of the disturbance zone. More work is planned to analyze these results and better conclusions will probably be presented in a later report.
6. Computer Modeling

Accurate computer modeling would save much time and money on future testing. Two methods were attempted to predict the stability of the coils; a zero-dimensional and one-dimensional model. The zero-dimensional model only considers the energy balance between the conductor and the helium at a cross section, while the one-dimensional model takes into account this energy balance, the helium flow, and the length of the disturbance.

These computer models were performed before all the samples data was known, and approximations were taken (ie for the sample coils resistance at 12 T). The zero-dimensional prediction was repeated after all information (ie limiting currents and resistivities are 12 T, superconducting transition) was available. However, because the one-dimensional model requires much CPU computer time, this model used the design specifications and was not repeated after receiving the experimental data. But, with these approximate values, the codes ability to predict stability between varying diameter strands can be judged.

6.1 Zero-dimensional Model

This model is a simple model which can be run with a personal computer. The program, JAERI's Quench Simulation (QS) code, automatically converges to the approximate stability margin with about 5 minutes of run time with a computer equipped with a math coprocessor.

6.1.1 Model

The zero-dimensional code uses the following model [23];

$$\rho_{cu} A_{cond} C_p \frac{dT_{cond}}{dt} = \rho_{cu} A_{cu} j_{cu}^2 - Q_{he} + Q_{ex}$$

and defines the temperature of helium by ;

$$A_{he} f_{he} \frac{d}{dt}(\gamma_{he} C_{pf} dT_{he}) = Q_{he}$$
and the heat transfer to helium by:

\[ Q_{he} = h \ (T_{cond} - T_{he}) \ P_c \ \rho C_p \]

\[ h = \frac{1}{2} \sqrt{\frac{\pi \, \lambda \, \gamma_{he} \, C_p f}{t_q}}. \]

The computer code calculates to 0.1 s at a specified time step. At 0.1 sec (stability is determined before this time [6]), if the conductor is still producing Joule heating, this condition is labeled a quench.

### 6.1.2 Results

The results of these model are summarized in figure 22 through 24. Note that for sample C's comparison, both the 5 cm and 10 cm disturbance length experimental stability is used for the comparison. The two prediction lines represent: (1) \( f_s = 1 \), which is the true zero-dimensional prediction, and (2) \( f_s = 0.75 \), which is the zero-dimensional prediction using a model where only the cooling perimeter and helium heat capacity are 75% efficient. This second model is the one currently used at JAERI for many of their zero-dimensional predictions.

![Graph showing input energy vs. normalized transport current](image)

**Figure 22**: Zero-dimensional stability prediction of sample A.
Figure 23: Zero-dimensional stability prediction of sample B.

Figure 24: Zero-dimensional stability prediction of sample C.
6.1.3 Discussion

The $f's = 1$ line predicts stability above the limiting current well for the three samples. Because this region's stability is just controlled by whether the conductor is above current sharing temperature after the pulse and induced flow has minimal effect [6], this zero-dimensional prediction performs well in this region.

For the well-cooled region below the limiting current, the performance of these equations is poor. Both $f$ lines on each graph predict quenches at lower input energies. In the well-cooled region, stability is controlled by induced flow, which is ignored in this analysis. However, this program does predict that sample A will have the highest stability, in agreement with experimental results.

As for the shape of the curves, the zero-dimensional prediction fairly accurately estimates the limiting current for all three samples.

For sample C, because the model is zero-dimensional, the prediction of the 5 cm and 10 cm disturbance length stability is the same, contradictory to experimental results. The $f's = 0.75$ prediction seems to better predict the stability of the 10 cm disturbance length sample. The zero-dimensional model seems more applicable to the 10 cm results, because, for the 5 cm disturbance length, much of the initially heated helium is flushed out the ends. Because the 10 cm disturbance length stability is better predicted by the $f's = 0.75$ line, this suggests that the cooling perimeter and helium heat capacity per cross section is approximately 75% efficient.

6.2 One-dimensional Model

The stability of the three coils was modeled using the one-dimensional code Quench Simulation of Forced-flow Conductors (QSFC), which was developed at JAERI. This code requires large CPU time. For the model of the coils tested, a model from time 0 to 0.1 sec (0 corresponding to start of input disturbance) the code required 20 minutes of CPU time on JAERI's supercomputing facilities.
After modeling the three coils stability with the preexisting program and getting poor results, the program was modified by changing heat transfer values "h" to agree with work presented in recent literature. The analysis was then redone, and better results were obtained.

6.2.1 Model

The one-dimensional computer code uses the following model of conductor energy equation and the three Navier-Stokes equations [24]:

   \[
   \gamma_{he} C_p f \frac{\partial T_{cond}}{\partial t} = \left( \frac{Q_{ex} + Q_j - Q_{he}}{A_{cond}} + \lambda_{cond} \frac{\partial^2 T_{cond}}{\partial x^2} + \frac{\partial \lambda_{cond}}{\partial T} \frac{\partial T_{cond}}{\partial x} \right)
   \]

2. N-S Continuity
   \[
   \frac{\partial (\gamma_{he} v)}{\partial t} = -\frac{\partial}{\partial x} (\gamma_{he} v^2)
   \]

3. N-S Momentum
   \[
   \frac{\partial}{\partial t} (\gamma_{he} v) = -\frac{\partial}{\partial x} (\gamma_{he} v^2) - \frac{\partial P}{\partial x} - \gamma_{he} F_f
   \]

4. N-S Energy
   \[
   \frac{\partial}{\partial t} \left[ \gamma_{he} \left( U + \frac{1}{2} v^2 \right) \right] = -\frac{\partial}{\partial x} \left[ \gamma_{he} v \left( U + \frac{1}{2} v^2 \right) \right] \frac{\partial}{\partial x} (Pv) + Q_{in} - \gamma_{he} v \frac{\partial \phi}{\partial x}
   \]

with

1. \( Q_{he} = h (T_{cond} - T_{he}) P_c \)

   \[
   h_k = 200 \frac{T_{cond}^4 - T_{he}^4}{T_{cond} - T_{he}} \quad \text{if } t_q \leq 1 \mu s
   \]

2. \( h = \begin{cases} 
   h_k = 200 \frac{T_{cond}^4 - T_{he}^4}{T_{cond} - T_{he}} & \text{if } t_q \leq 1 \mu s \\
   h_t = \frac{1}{2} \sqrt{\frac{\pi \gamma_{he} C_p f}{t_q}} & \text{if } h_t \geq h_s \\
   h_s = 0.023 \Pr^{0.4} \Re^{0.8} \frac{\lambda}{D_h} & \text{if } h_t \leq h_s
   \end{cases}
   \]

After poor results were obtained using this model initially, the model was slightly altered by changing the h value to agree with
work by Agatsuma [7] and by Shanfield [25]. The heat transfer coefficient was modified so that

\[ h = \frac{h_k h_t}{h_k + h_t} + h_s \]

with

\[ h_k = 200 \frac{T_{\text{cond}}^4 - T_{\text{he}}^4}{T_{\text{cond}} - T_{\text{he}}} \]

\[ h_t = \sqrt{\frac{\lambda_{\text{he}} C_p f}{\pi t_q}} \]

\[ h_s = 0.023 \Pr^{0.4} \Re^{0.8} \frac{\lambda}{D_h} \]

Note that the transient heat transfer is modified slightly.

6.2.2 Results

The program QSFC was first used without modification to attempt to model the sample coils' stabilities at a few transport currents. This model gave poor results. Because of this, the mesh was altered slightly and the \( h \) values were modified. With this new model, much better results were obtained.

Note that these runs were done with information prior to testing, and therefore only approximations, on data such as resistivity at 12 T, were used.

6.2.2.1 Existing "\( h \)" Program

The run of this program produced poor results, with the difference between the three coils predicted stability being only very minor. A summary of the results of the predicted stability for the three coils at transport current of 2083 A, 3333 A, and 4167 A (best fit lines are draw from these points) is on figure 25 (for an example of QSFC printout, see Appendix). The three lines represent the predicted stability.

6.2.2.2 Modified "\( h \)" Program

After modifying the programs, much better results were obtained. Prediction were done for sample A, B and C at the
Figure 25: One-dimensional stability prediction using the original "h" and 5 cm minimum length mesh.

Figure 26: One-dimensional stability prediction using modified "h" and 1 cm minimum length mesh.
transport current of 2083 A, for sample A at 3333 A and 4167 A, and for the sample C 10 cm disturbance length at 2083 A.

At 2083 A, the prediction is 2 to 3 times greater than experiment. In the past QSFC has always predicted a much stabler conductor. At this current, the experimental stability difference of sample B's and C's, compared with A's stability, are about 75% and 40%, while the computational stability is 90% and 63%. The stability does decrease with increasing strand diameter.

At 3333 A, samples A prediction is much larger than experimental results. (See figure 26 for QSFC prediction of coils A stability.) The computational stability margin predicts the limiting current at a higher current than experimental results.

At 4167 A, above the limiting current, sample A's prediction is very accurate.

For predictions on heated length stability dependence, the code predicts the 10 cm disturbance length to be about 85% less stable, when experimental results show it 55% less stable.

6.2.3 Discussion

The modified "h" produced better results. However, a direct comparison is unfair because the mesh was also changed. The original mesh had its heated zone lengths as 5 cm, where as the new mesh had lengths of 1 cm.

The one-dimensional program QSFC has always predicted much more stable conductors than experiments have shown, as is the case for the samples' models. However, QSFC did predict less stable conductors as the strand diameter increased and as the heated zone increased from 5 to 10 cm.
7. Comparison of Diameter Varying Properties

The magnet designer needs to make a decision on the diameter of strands to use in the cable-in-conduit superconductor. The choice of diameter is limited by manufacturing considerations. Within these possible choices, differing diameter strands will affect properties such as;

1. Stability
2. Conduit helium pumping power
3. Mechanical rigidity
4. Disturbance energy during possible strand movement
5. Cost

The two most important of these properties seem to be stability and pumping power. To judge the mechanical rigidity of a strand, the deflection under a force can be estimated by [26]

\[
deflection \propto \frac{\text{force} \times \text{length}}{\text{moment of inertia}}
\]

Some rough calculations with the sample coil parameters show this deflection to be close for strand diameters 1.1 to 1.6 mm. Disturbance energy during a strand movement has not been studied in detail; therefore, conclusions cannot be made. As for cost, on a low volume product such as a fusion reactor, the cost difference to produce the strands should not be a major design criteria.

As for stability, the stability increases with decreasing strand diameter as predicted computationally and experimentally. Smaller diameter strands are favorable because of the larger cooling perimeter per cable cross section.

Pump power, on the other hand, if the mass flow rate of helium is the same, increases with decreasing strand diameter. The increased friction surface of small diameter strands decreases the Reynold's number. The friction factor increases as a function of Reynold's number, approximated by [27]

\[
\frac{1}{\sqrt{f_D}} = 0.87 \ln(Re\sqrt{f_D}) - C_1
\]
with $C_1$ being a constant. From data taken from the US-DPC and DPC-TJ experiment, this $C_1$ variable is set at 3.0. The pressure drop in the conductor's conduit can be calculated by [26]

$$\Delta P = f_D \frac{L_{\text{cond}}}{D_h} \frac{1}{2} \frac{1}{g \gamma_{he}} \left( \frac{\dot{m}}{A_{he}} \right)^2.$$ 

Then, the electrical power supplied to the pump $W_{pe}$ is derived by [26]

$$W_{pe} = f W_{pa} = \frac{1}{\eta} \frac{\dot{m} \Delta P}{\gamma_{he}},$$

can be derived, which is directly proportional to this pressure difference. This equation is graphed verse strand diameter in figure 27. Using specifications preliminary specified for the ITER project [28], the electrical power required for the pumping of this helium is $W_{pe} = 10$ MW. This is a large energy, and therefore lowering the friction factor is important for economical operation.

Therefore, the magnet designer must measure the relative costs of each of these factors when making his decision on the conductor parameters.
Effect of Strand Diameter on Pump Performance

Figure 27: Sketch of forced flow helium pump power or pressure difference verse strand diameter.
8. Conclusions

The main goal of this series of experiments was to study the effect of strand diameter on stability experimentally. This series of experiments compared different coils stabilities using inductive heaters. By using the method of calibrating these heater at 0 T and extrapolating numerically to 12 T, results have fair agreement with stability theory. When compared using normalized transport current with sample A's ($d_{st} = 1.07$ mm, $P_c = 90.8$ mm) stability margin in the well-cooled region, sample B ($d_{st} = 1.32$ mm, $P_c = 74.6$ mm) is slightly less stable and sample C ($d_{st} = 1.60$ mm, $P_c = 60.3$ mm) is about 50% as stable. These experimental results have fair agreement with computer numerical analysis. Small diameter strands, which allow that cable to have a greater cooling perimeter, cause the conductor to be more stable.

For the largest strand diameter coil, stability was also measured using a 10 cm disturbance length instead of the usual 5 cm length. Comparison of the measured stabilities from the tests of these two different disturbance lengths shows the 10 cm length to be less stable at currents in the well-cooled region. Voltage traces show that the 10 cm case received better cooling initially shrinking the initial normal zone to a larger percent, but that this normal zone eventually grew before 100 ms. The least stable disturbance length seems to be a function of imposed and induced flows. (A more detailed analysis will be performed for later reports.)

Sample B and sample C had distinct limiting currents while sample A’s is not very distinct. Dresser's relation for limiting current is in good relation to experimental results, and, therefore, $I_{lim} \propto P_c$.

Zero-dimensional computer stability prediction predicted stability above the limiting current well, but below the limiting current could only roughly predict stability. This code is also inadequate to describe the differences in stability for coil C with differing disturbance lengths. Much trouble was experience using the one-dimensional code, but, even though all the coils predicted stability was much greater, predicted the smaller diameter strands to be more stable and the 5 cm disturbance length to be more stable than the 10 cm.

This is the first report that presents the results of these stability tests performed with three different cooling perimeter samples. These results are preliminary and will be developed for a later report. Validity of computing 12 T inductive heater calibration curve from 0 T curves will also be checked experimentally.
9. Recommendations

Trouble was encountered when trying to compare the stabilities of different samples. It is felt that this is caused by the inaccuracy of the inductive heater calibrations. Inductive heaters have in the past been calibrated at zero field, and then these same energy input calibrations used with a background magnetic field imposed. This seems to be inaccurate because of the resistivity changes at high field. Experiments are planned at JAERI to study the effect of varying background magnetic fields on inductive heater input energies.

For the magnet designer, one of the variables when designing a conductor is strand diameter. Using results obtained from an averaged computed 12 T calibration curve, experiments show good agreement with theory; the stability increases for smaller diameter/higher cooling perimeter strands. However, as strand diameter increases, the pump power for the forced flow helium increases. Therefore, the designer has to weigh the relative costs of these two factors to choose the optimal conductor.

The experiment of sample C also showed that the length of the disturbance zone is an important criteria when specifying required stability of a conductor. Further experiments should be conducted to study this question.

The one-dimensional stability code at JAERI, Quench Simulation of Forced Flow Conductors, needs also to be improved. As has always been the case for models of other coils, this code predicted a conductor which is much stabler that experimental results.
Acknowledgements

I would first like to thank Dr. Tsuji and Dr. Shimamoto for giving me the chance to work at JAERI and making the transition easier.

Much thanks is due to Nishi-san and Koizumi-san with whom I worked with on this project. Nishi-san was always available for my unending questions. Koizumi-san was a great help in the lab and out. For computer simulations work, I would also like to thank Yoshida-san who spent much time helping interpret codes documented in Japanese, and to Harada-san who solved many problems related to the supercomputing system. Help from other people in the lab is too numerous to mention, and I hope they will know my appreciation.

I would also like to thank Dr. Iwasa for allowing me the opportunity to work on my masters degree at JAERI, which gave me a much larger education than superconducting magnets.

Also, I am grateful to the USDOE who funded my work and tuition. Also thanks to the MIT-Japan program for their help and training to make living in Japan fun and informing.

But, most of all, I need to thank my sister Anne. Hopefully, this work will help her dream of preventing further destruction of the nature she loved so much. I just can't express how I feel in words, but I'll always remember and love.
References


Appendix

This appendix presents some example printouts from the JAERI's one-dimensional stability code QSFC. For each example, three-dimensional graphs of (A) temperature, (B) pressure, (C) velocity, (D) Joule heating, and (E) conductor temperature are given verse time and position along the 715 cm conductor. Four series of printouts are presented:

(1) Example of recover printout of one-dimensional code using the existing "h" and 5 cm minimum mesh lengths. Transport current is 2083 (A-E)

(2) Example of near stability margin recover printout of one-dimensional code using the modified "h" and 1 cm minimum mesh lengths. (A-E)

(3) Example of near stability margin quench printout of one-dimensional code using the modified "h" and 1 cm minimum mesh lengths. (A-E)

(4) Example of high current quench printout of one-dimensional code using the modified "h" and 1 cm minimum mesh lengths. (A-E)
Printout 1: Example of recover printout of one-dimensional code using the existing "h" and 5 cm minimum mesh lengths. Transport current is 2083 (A-E)
Printout 2: Example of near stability margin recover printout of one-dimensional code using the modified "h" and 1 cm minimum mesh lengths. (A-E)
Printout 3: Example of near stability margin quench printout of one-dimensional code using the modified "h" and 1 cm minimum mesh lengths. (A-E)
Printout 4: Example of high current quench printout of one-dimensional code using the modified "h" and 1 cm minimum mesh lengths. (A-E)