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HEAT INDUCED FLOW EFFECTS ON HEAT TRANSFER PROPERTIES OF A PULSED SUPERCONDUCTOR

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Heat transfer properties of a pulsed conductor, called JA-10, were measured and important effects by heat induced flow were found.

JAERI has developed the conductor JA-10 for research and development of superconducting poloidal coils for tokamak reactors. JA-10 is a 10-kA, 7-T pulsed conductor with NbTi bundles around a stainless steel flat core. Heat transfer properties from the surface of this conductor is an important basis for its stability during pulsed operation, therefore we measured the heat transfer property under the same condition as a wound coil.

By this experiment, it was clarified that turbulent flow in the uninterupted vertical cooling channels strongly enhance heat transfer properties of a pulsed conductor like JA-10.

Keywords: Superconductor, Pulse, Poloidal, Heat Transfer, Helium, Bubble, Stability

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超電導パルス導体の冷却熱流束に及ぼすヘリウム誘起流の効果

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（1982年7月30日受理）

JA－10と呼ばれるパルス導体について，冷却熱流束を測定し，熱せられたヘリウム誘起流による効果を明らかにした。

原研では，トカマク用超電導ポロイダル・コイルの研究開発のためにJA－10導体が製作された。この導体は，7Tで動作する10kAのパルス導体で，ニオブ・チタンのバンドルがステンレス鋼の平板のまわりにまきつけられた構成となっている。パルス動作中の安定性を確保する上で，導体表面からの冷却熱流束の重要度が高いため，コイルに巻かれた場合と同等の条件下で熱流束の測定を行った。

この実験の結果，垂直冷却チャネル内に誘起されるヘリウム流によって，JA－10の様なパルス導体の冷却熱流束特性は，大巾に向上する事が明らかになった。

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1. INTRODUCTION

In a real magnet system, the body force acting on a conductor due to the radial and axial components of the magnetic field cause the individual conductor strands and twisted cables to press against one another. One can anticipate that under such conditions the heat transfer properties of the conductor will differ from that of the conductor simply immersed in liquid helium. In particular, under this kind of self compaction, the surface cooling will decrease due to reduced surface area, and the conductive heat transfer will increase due to decreased contact resistance between ajacent conductor twisted strands.

Basically, the question is, which effect will predominate: decreased surface cooling or increased conduction. The results indicated a third effect, due to heating induced turbulent flow in the uninterupted vertical cooling channels, strongly enhanced cooling.

2. DESCRIPTION OF EXPERIMENT

2.1 APPARATUS

An experiment was carried out to measure the influence of the conditions described above using mechanical forces to press the conductors together. A schematic diagram of the mechanical apparatus is shown in Fig. 1 and Fig. 2, which is a detailed drawing showing the five JA-10 second level cables (see Fig. 3), the cooling channel arrangement, and the manner of compacting the cables.

2.2 EXPERIMENTAL PROCEDURE

An insulated stainless steel wire which passes through the center of each twisted cable is used as a heater (see Fig. 3). These heaters can be energized separately or in various combinations as desired. Generally, either the center heater (referred to as H3), the top-middle-bottom heaters (H135), or all five heaters (H12345) were energized. The temperature of the conductor were monitored using gold-chromel thermocouples. The temperature of the conductor is plotted as a function of the heat input per unit length (W/cm) at a variety of different compaction loads.

2.3 EXPERIMENTAL PARAMETERS

2.3.1 Wire configuration

Five second level cables from the JA-10 pulsed field coil conductor were stacked in the apparatus to be compacted. The details of this conductor, rated for 10 kA, are shown in Fig. 3.

2.3.2 Heating

Heating per unit length is a function of heater current, where

ρ(stainless steel at 4.2 K) = 5.3×10^{-7} ohm-m

Diameter (stainless steel heater) = 10^{-3} m

$$\frac{Q}{L}\ (\text{W/cm}) = \frac{I^2 R}{L} = \frac{I^2 \rho L}{L\ A} = 6.7 \times 10^{-3}\ I^2 \times \frac{1}{1 - R_{\text{coverage}}}$$

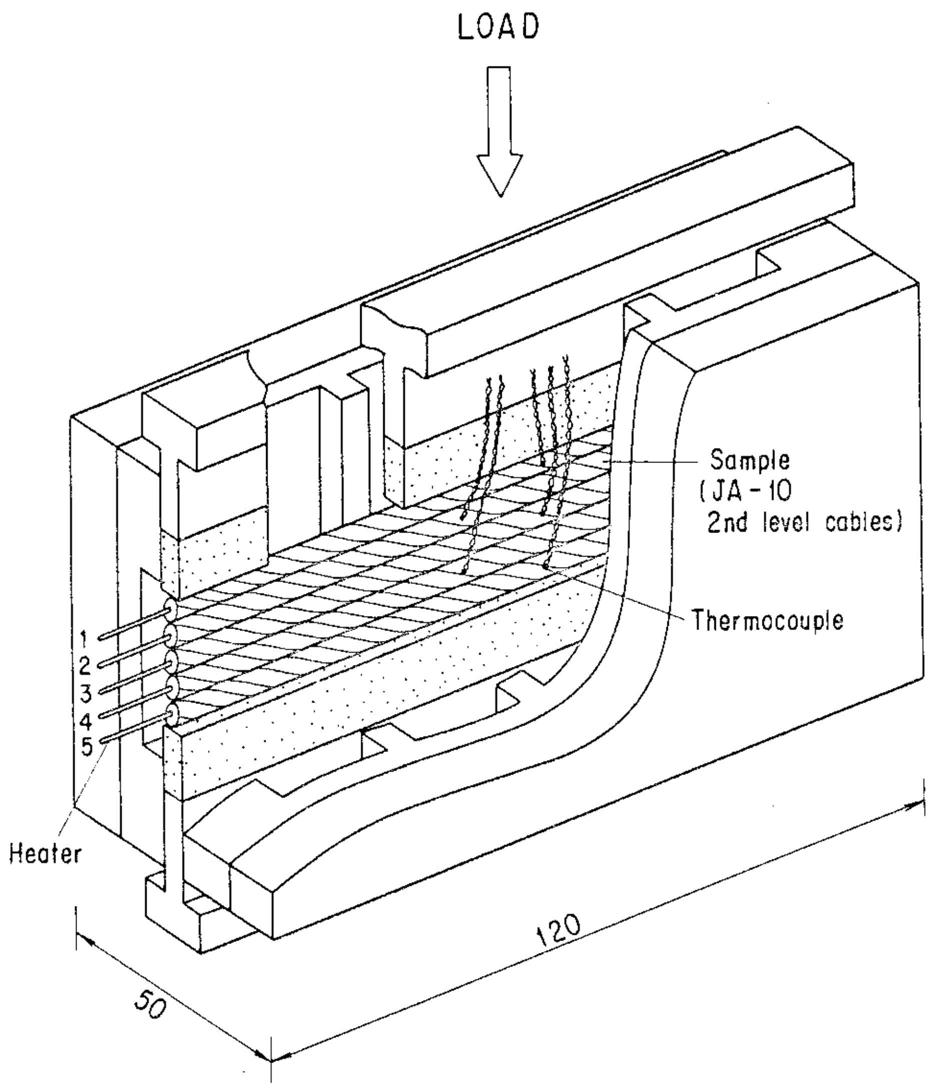

Fig.1 Shematic diagram of conductor compaction apparatus

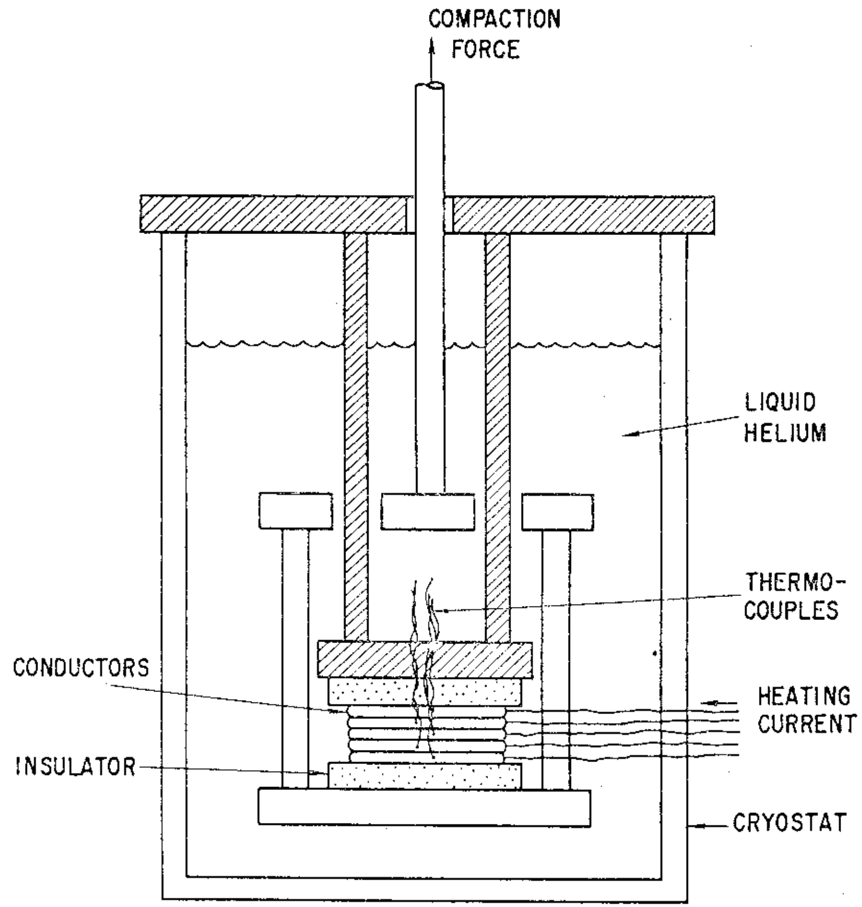

Fig.2 Detailed view of the wire compaction apparatus

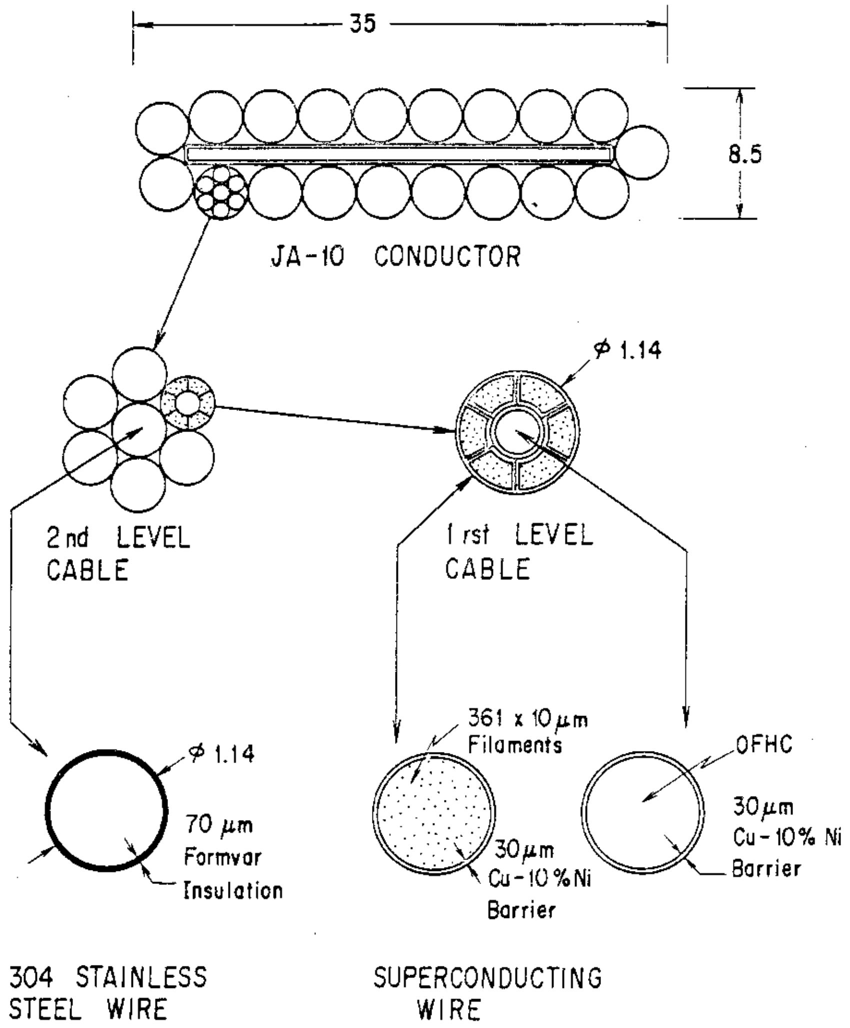

Fig.3 Elements of the JA-10 pulsed field coil conductor

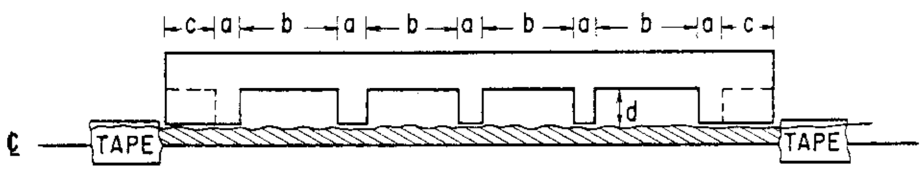

Fig.4 Cooling channel geometry

2.3.3 Surface Area Coverage

Part of the conductor surface area which is potentially available to heat transfer is blocked by structural material, labeled "a" in Fig. 4. Several methods are used to determine coverage area. In this case, we use the ratio,

$$R_{coverage} = (A_{covered}) / (A_{total})$$

2.3.4 Cooling channel depth: d = 5.0 mm

2.3.5 Compaction Pressures:

$$\text{Pressure} = \frac{\text{Load}}{\text{Loading Area}} = \frac{L}{350\ mm^2} \quad (kG/mm^2)$$

3. RESULTS

Two strong effects were observed, 1) the change in the cooling due to compaction, and 2) the change in cooling due to "heat induced turbulent flow."

3.1 Compaction Effect

The effect due to compaction can be observed in Fig. 5 when conductor #3 is the only one conductor being heated as the load is varied. Here, cooling increases with loading because improved conduction to the adjacent cold conductors spreads the heat over a larger volume and surface.

Naturally, when all conductors are being heated, compaction reduces cooling because heat does not flow to adjacent conductors since they are all close to the same temperature, but the total surface area has been reduced due to compacting. This is observed in Fig. 10 as the load is raised from 0 to 250 kG.

Ignoring any heating induced flow effects on conductor #3, Fig. 10 is also a good example of how the surface cooling area changes during loading since heat condition to adjacent conductors is minimized .

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The greatest reduction in cooling surface area occurs at low loads (below 125 kG or 3.5 MPa). Thereafter, the change in the surface area due to additional compaction is very small, as is the change in the heat transfer characteristics.

3.2 "Heat Induced Turbulent Flow" Cooling Effect

Improved cooling is caused by the helium stream (liquid and gaseous) flowing in the continuous, vertical, cooling channel. The velocity of this stream is influenced by the thermal expansion of the heated helium and the viscosity of the helium at different densities (chimney effect). This heating induced turbulent flow, "HITF" changes the characteristic shape of the heat transfer curves, as shown in Fig. 6 and improves cooling.

This is observed in Fig. 7 where the shape of the heat transfer changes for conductor #3, and cooling is improved by the flow caused by heating the conductors below it (conductor #5 and conductor #4 & #5 in this case).

The strong influence of heating induced turbulent flow on conductor #3 is witnessed by the fact that when H135 and H12345 are energized, both three times and five times more energy are being freed into the system, yet the temperature of conductor #3 is significantly lower.

Fig. 8 shows curves for conductor #5 which has no heated conductor below it, There is only a minor change in the shape of these curves and in the heat transfer characteristic under the three different heating conditions (H5, H135, and H12345) at zero load.

Figs. 9, 10, and 11 show the combined effect of the heat transfer characteristic under the influence of both compaction and heat induced flow.

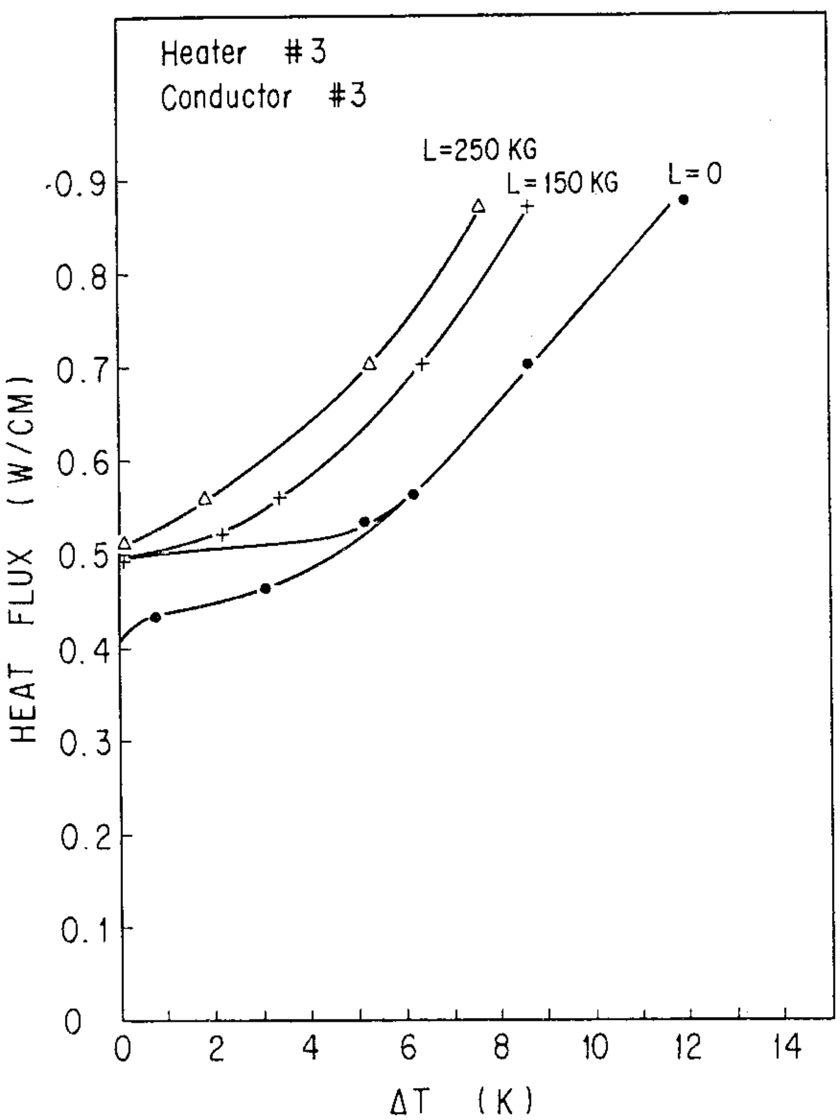

Fig.5 Heat transfer characteristics-Compaction only

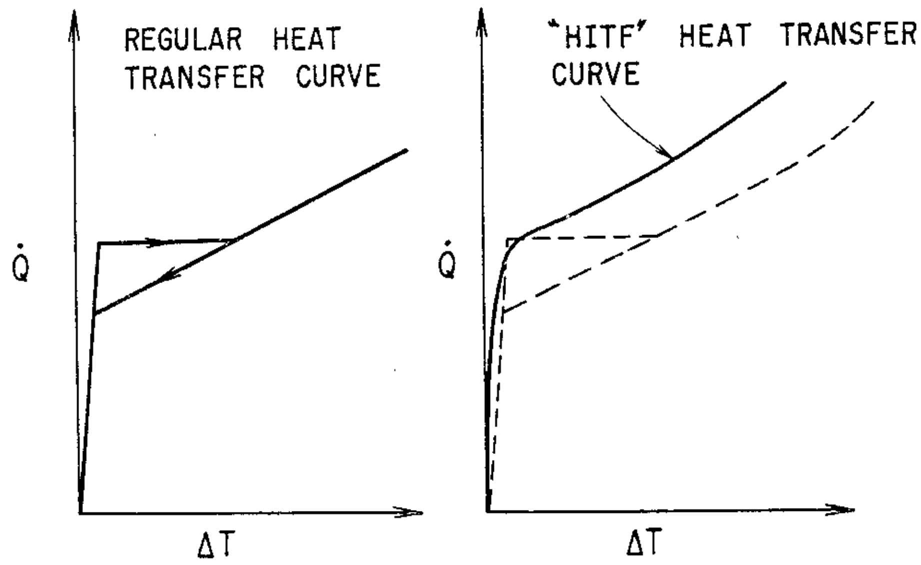

Fig.6 Effect of Heat Induced Turbulent Flow (HITF)

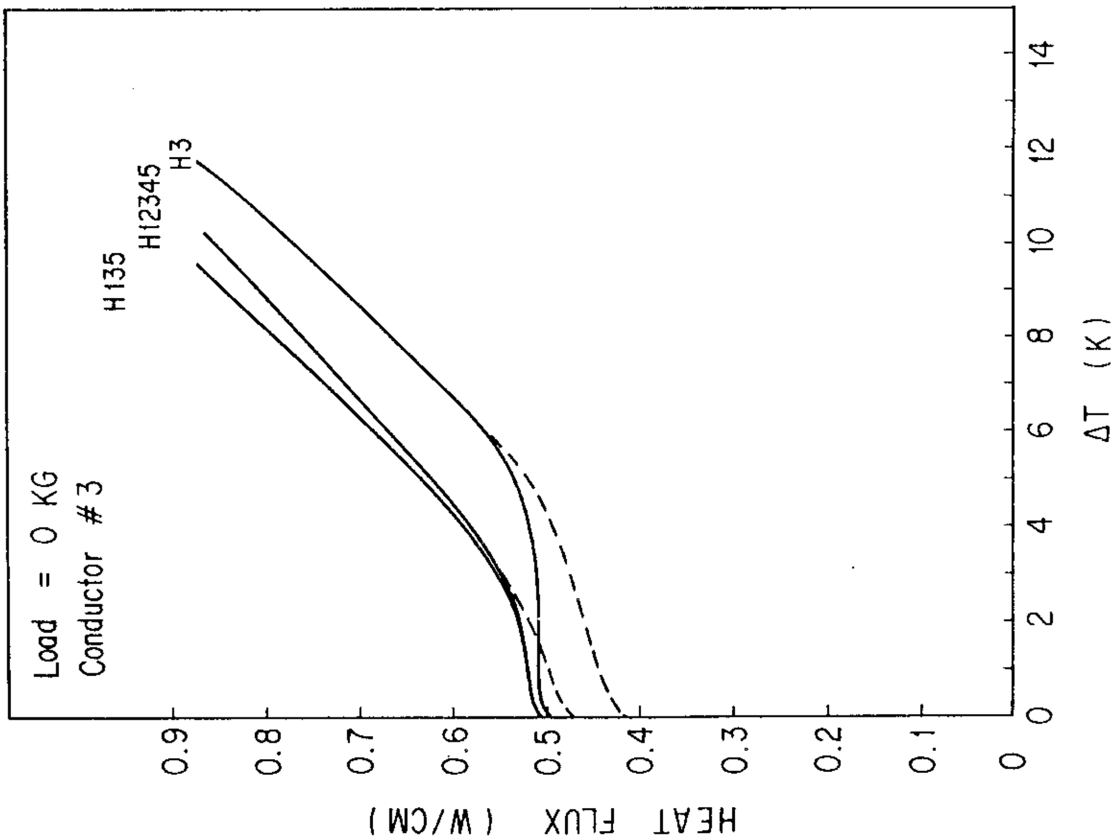

Fig.7 Heat induced turbulent flow heat transfer

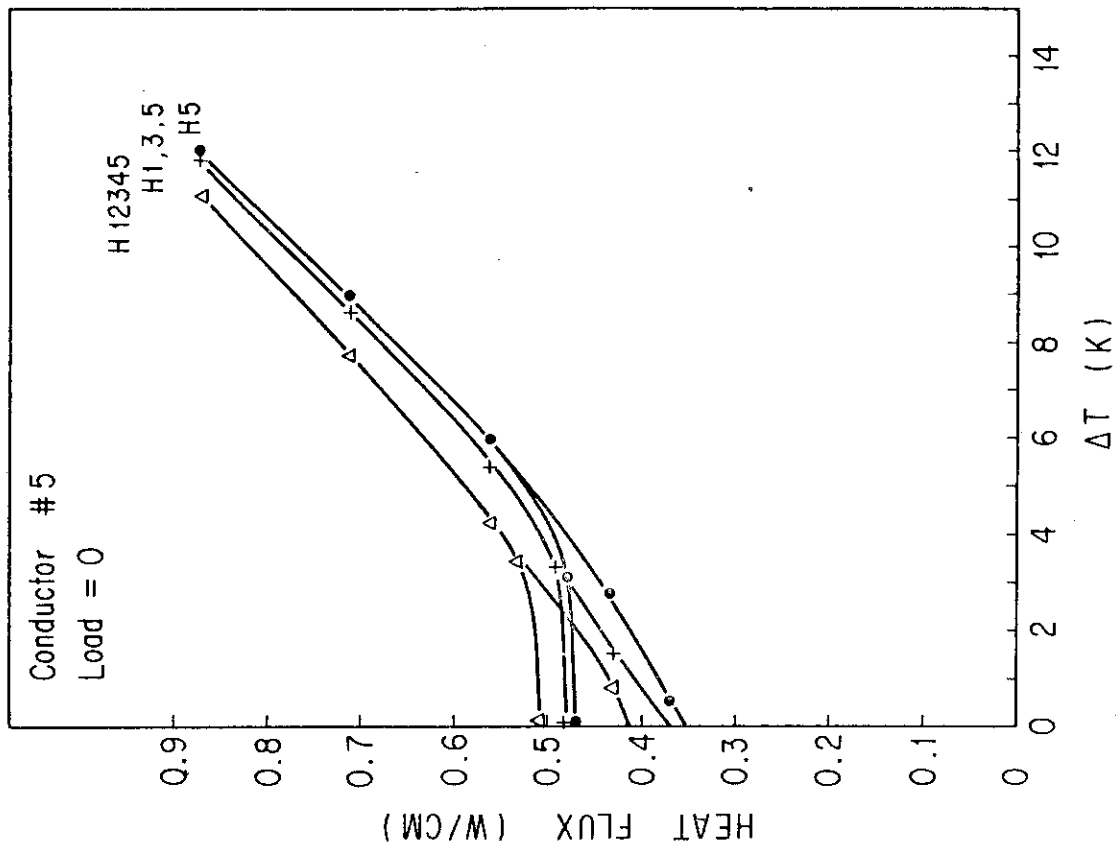

Fig.8 Minor influence of heat induced turbulent flow heat transfer on conductor #5

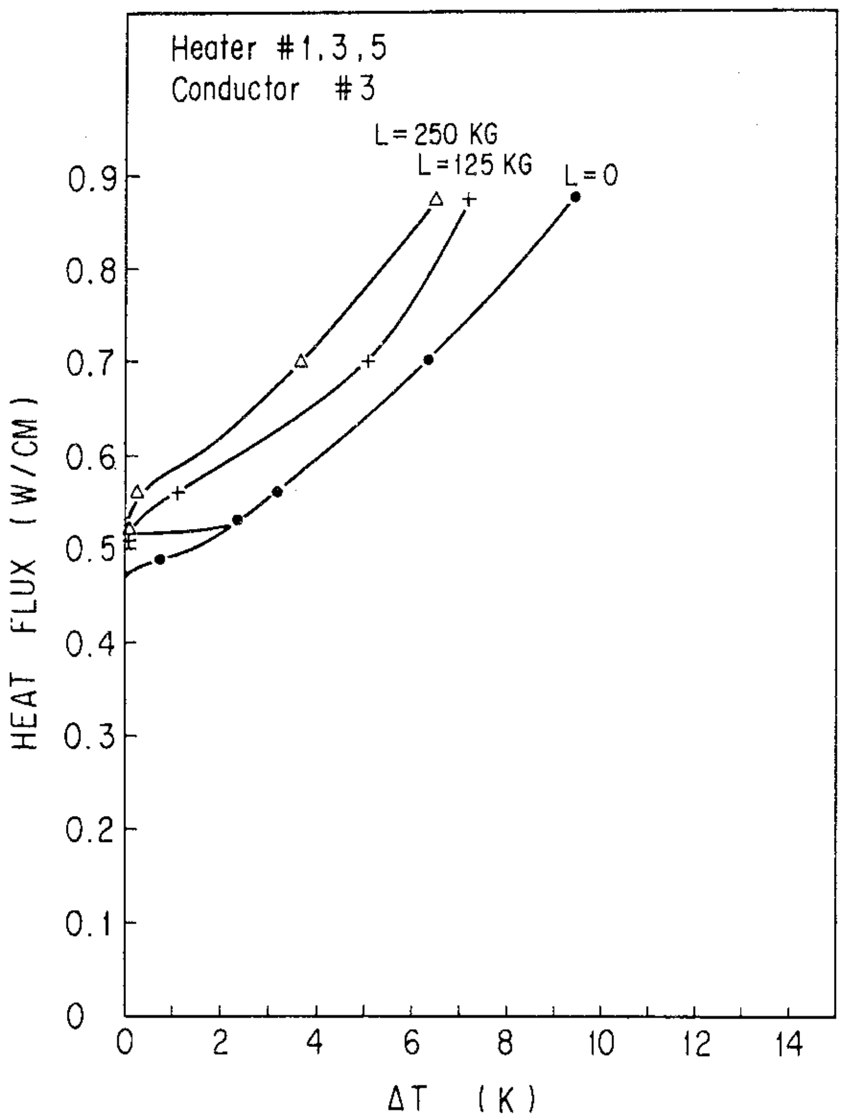

Fig.9 Heat induced turbulent flow plus compaction effect on heat transfer characteristics

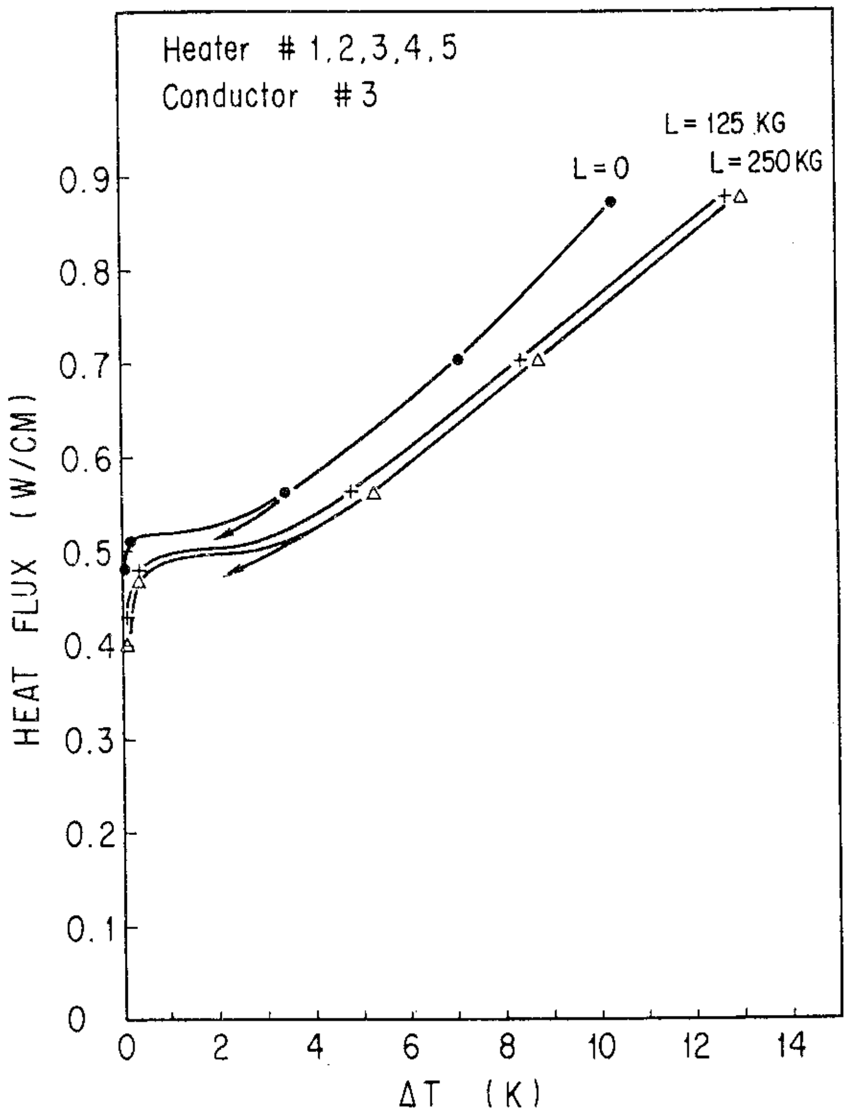

Fig.10 Heat induced turbulent flow plus compaction effect on heat transfer characteristics

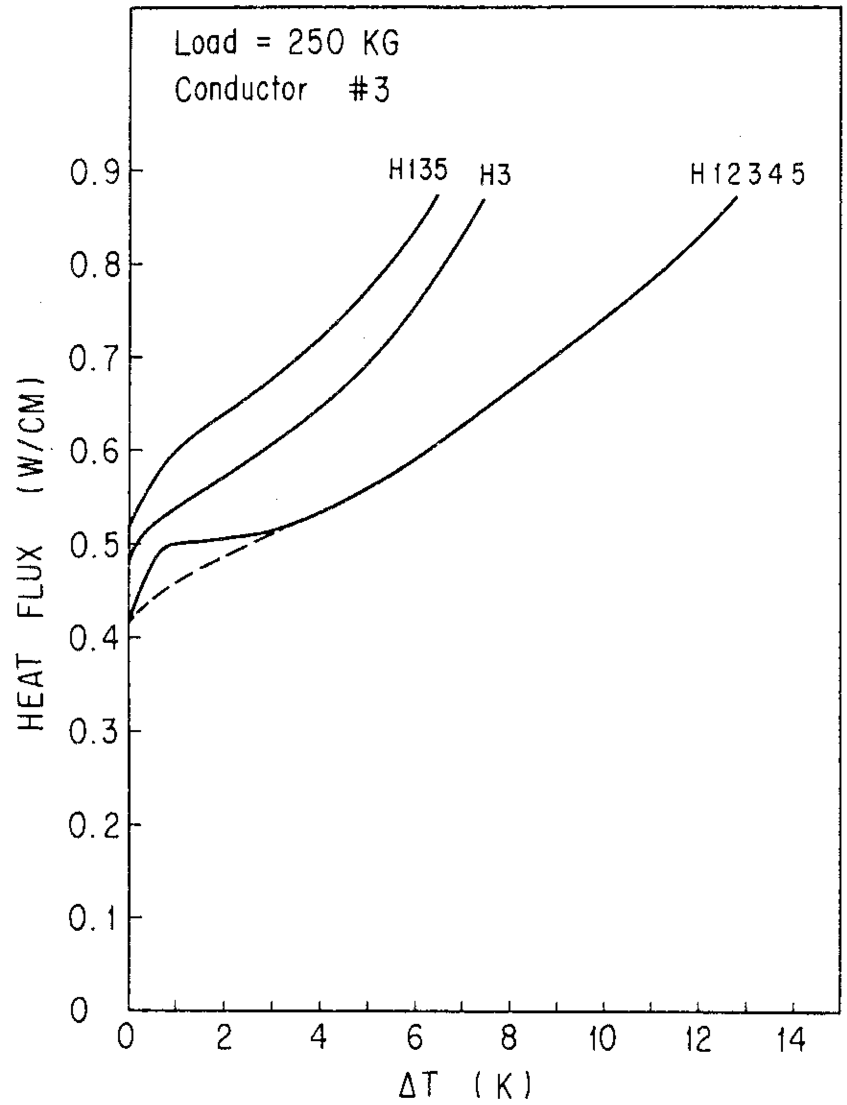

Fig.11 Heat induced turbulent flow plus compaction effect on heat transfer characteristics

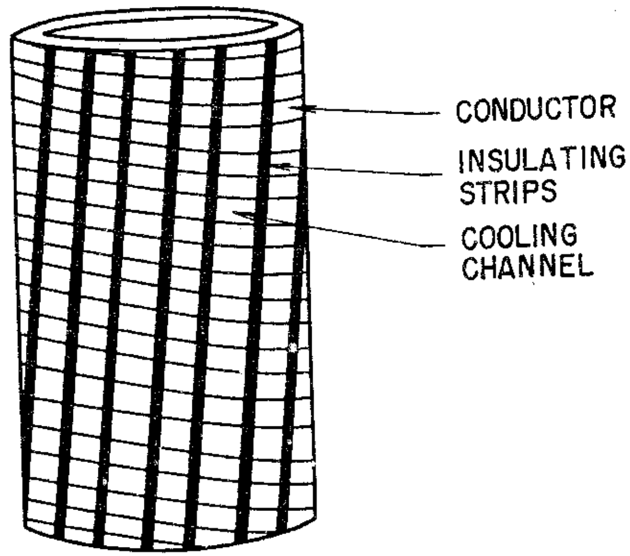

Fig.12 JAERI's single layer winding for stability test

4. DISCUSSION

Compaction can both improve and degrade heat transfer depending on the circumstances. However, heating induced flow would seem to be beneficial at anytime and every effort should be made to try to create its formation within the cooling channels of a magnet.

It appears that long, uninterupted, vertically oriented cooling channels best promote this type of cooling behavior. In general, such vertical cooling channels are easily achieved in helically wound solenoids such as pulsed field coils, because long insulating strips normally run in the axial direction or are wound at a steep angle. It is not so easy to incorporate heating induced flow in pancake type coils. However, if the flat side of the pancakes are in the vertical plane (as for toroidal field fusion magnets), it should be possible to create this behavior. One such arrangement will be described later in this section. Pancake windings stacked in the horizontal plane seem to be least accomodating because the vertical cooling channels between turns are not only short but also interupted by the large horizontal space between pancakes. Heating induced flow has been found to exist inside "cable in conduit" conductors.[1,2] In fact it is this type of cooling which allows these conductors to absorb large heat inputs without the need of imposing helium flow in the conduit by means of pumping.

Improved stability was reported in several single layer test coils used by JAERI to investigate the performance of the conductor for use in the Japanese LCT coil.[3] These single layer coils were wound helically and incorporated thin strips running up the outside of the solenoid at a steep angle to form cooling channels, as shown in Fig. 12.

An experiment was carried out to help explain why the coil demonstrated stability beyond that which could be expected from the heat transfer properties of a conductor sample. In this experiment the heat transfer characteristic of one conductor sample was measured while heaters were energized in conductor samples located underneath the test sample. The change in the heat transfer characteristic was similar to the change described here, and chimney effect type flow in the channel was suggested as the reason why.

Since there is strong evidence to suggest that induced flow in a continuous cooling channels promotes enhanced stability, a cooling channel pattern is proposed to be applied to vertically oriented pancake windings to exploit this additional cooling effect. The objective of this pattern is to direct the induced flow from a hot portion along a conductor turn, back upon itself in order to prohibit further normal propagation. Circular pancakes with pancake to pancake spacers running out radially, as in Fig. 13, are not efficient in utilizing heating induced flow because a normal zone must propagate one full turn before intersecting a cooling channel with heat induced flow. In addition, only the top and bottom section have vertically oriented cooling channels.

Fig. 14 displays a spacer pattern to be applied to the front and back of a circular pancake which should quickly redirect induced flow to portions along the conductor turn which have normalized. By doing so, propagation should be held to one half turn or less. As an example, if the conductor becomes normal at a point A, heating at this point should also induce flow in the channel which will act to enhance cooling at the point C, thus retarding propagation in that direction. If the normal zone propagetes to the point B, heating at B will induce flow in the channel acting to cool point A. The same is true on the back side of the pancake. Should the normal zone propagate as far as the points E and G, induced flow should be set up in the cooling channels to cool the conductor at points D and F, helping to self-stabilize the conductor.

The organized surface pattern might also act ot produce strong bottom to top flow currents during global disturbances (such as plasma heating disturbances in fusion machines) which would be beneficial for rapid recovery to the superconducting state.

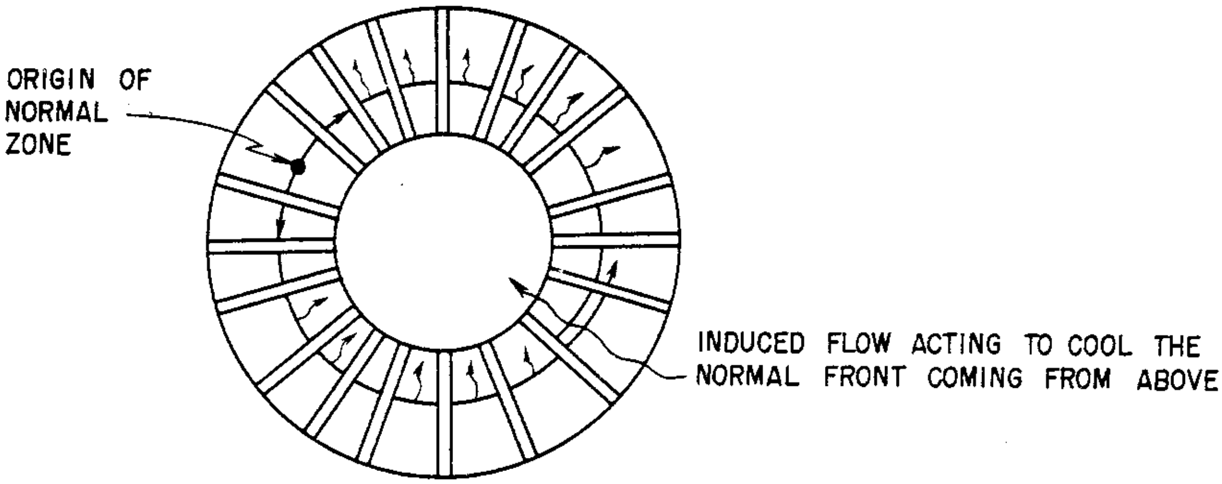

Fig.13 Effects of helium flow on propagating normal zone

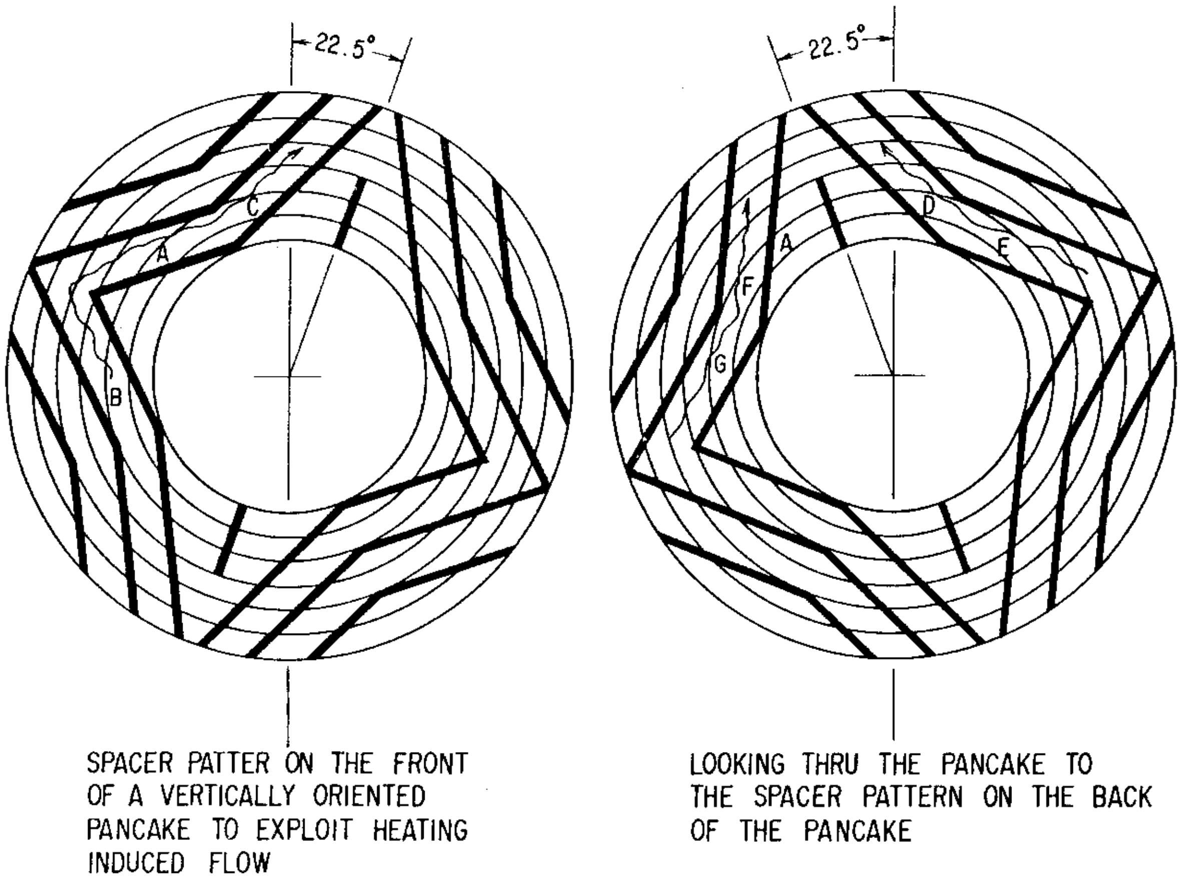

Fig.14 A possible spacer pattern to obtain enhanced stability by induced flow

5. CONCLUSIONS

1. Analysis of magnet stability can not be performed from heat transfer characteristics of short samples merely immersed and heated in liquid helium for certain kinds of conductors and winding configurations: particularly for cable type conductors and windings with long vertically oriented cooling channels.

2. Compaction of twisted cable elements of a bundle type conductor (like JA-10) will occur due to the interaction of the radial component of the magnetic field and the current. To take this into account when interpreting stability measurements, the following points should be kept in mind:

   a) Only a small compaction pressure is necessary to cause a large initial change in the heat transfer characteristic (less than 3.5 MPa in this case).

   b) Compaction improves heat transfer if the heating is localized (i.e. a slip event) because the improved transverse heat conduction helps diffuse the input energy to other conductor strands.

   c) Compaction will degrade heat transfer if heating is global (as when exceeding the critical current) because of reduced cooling surface area.

3. Heat induced flow will appear whenever long, continuous, vertically oriented cooling channels are available. This is because the flow velocity in the channel increases the overall heat transfer coefficient. This is related to the heating induced flow seen in cable in conduit conductors at zero pumping velocity.

   a) Coils constructed with vertically oriented pancakes, like the Cluster Test Coils [4] and Japanese LCT coil, could benefit from heat induced flow heat transfer if the long insulating strips epoxied to their surface were designed to exploit heating induced flow.

   b) A series of experiments should be conducted to verify this hypothesis for several different cooling channel patterns.

   c) Analysis should be carried out to determine the relation between parameters (channel depth, width, length, helium velocity, etc.) which can be used to optimize the channel configuration.

4. It's time to put heat induced flow to work in enhancing the stability of pool-cooled coils. Cooling channels should be built to exploit this phenomena.

REFERENCES

1. Y. Iwasa, M. O. Hoening, and D. B. Montgomery, "Cryostability of a small superconducting coil wound with cabled hollow conductor", IEEE Trans. MAGN. MAG-13 (1977) p678
2. J. R. Miller, J. W. Lue, S. S. Shen, and L. C. Lottin, "Measurements of stability of cabled superconductors cooled by flowing supercritical helium", IEEE Trans. MAGN, MAG-15 (1979) p351
3. M. Nishi, T. Ando, K. Yoshida, K. Koizumi, and S. Shimamoto, "Roughened surface study on Japanese test coil for the Large Coil Task", IEEE Trans. MAGN. MAG-17 (1981) p904
4. S. Shimamoto, T. Ando, T. Hiyama, H. Tsuji, E. Tada, M. Nishi, K. Yoshida, K. Okuno, K. Koizumi, Y. Takahashi, T. Kato, K. Oka, Y. Ibaraki, Y. Sanada, and K. Yasukochi, "Construction and operation of the Cluster Test Facility", IEEE Trans. MAGN. MAG-17 (1981) p494