# Lawrence Berkeley National Laboratory
**Recent Work**

**Title**

PERFORMANCE OF SUPERCONDUCTING NbTi AND NbZr INORGANIC SOLENOIDS

**Permalink**

https://escholarship.org/uc/item/0797m2vv

**Author**

Hintz, R.E.

**Publication Date**

1967-08-01

# University of California

# Ernest O. Lawrence
# Radiation Laboratory

PERFORMANCE OF SUPERCONDUCTING NbTi AND NbZr
INORGANIC SOLENOIDS

R. E. Hintz

August 1, 1967

# DISCLAIMER

# UNIVERSITY OF CALIFORNIA

# PERFORMANCE OF SUPERCONDUCTING NbTi AND NbZr INORGANIC SOLENOIDS

R. E. Hintz

August 1, 1967

# PERFORMANCE OF SUPERCONDUCTING NbTi AND NbZr INORGANIC SOLENOIDS

R. E. Hintz

Lawrence Radiation Laboratory
University of California
Berkeley, California

August 1, 1967

## INTRODUCTION

Recent developments in coil construction and NbTi superconductors have resulted in magnets described by the following distinctive characteristics.

1.  Reliable. Coils have consistently operated at the high short-sample limit of the conductor. The coils are self-protecting and may be safely transitioned while partially submersed in liquid helium.

2.  Compact. Average current densities of 20,000 to 55,000 A/cm$^2$ were produced with fields from 40 to 70 kG and bores up to 5 in.

3.  Economical. Below 80 kG, NbTi superconductors operating near the short sample limit offer significant savings when compared with presently-available NbZr and Nb$_3$Sn conductors.

4.  Electrically insulated. Coils can be charged to full current within 1 min without training effects. There are no shunt currents and the field corresponds directly with the charge current.

5.  Improved performance below 2°K. Operation in helium II results in an increase in the critical current and permits high charge rates.

6. Strong. The ductile NbTi copper-clad conductor will withstand large hoop stresses. Fiberglass cloth maintains electrical insulation between layers under high compressive loads.

7. Moderate currents. Reduces expense of the power supply and lead losses. The cost of the present conductors compares favorably with large conductors.

## COIL CONSTRUCTION

The superconductor selected for recent coils was Supercon Nb48%Ti (T48B). A copper jacket is drawn with the NbTi and results in a metallurgical bond between them. The quality of this bond is probably responsible for the substantial improvement in stability of this conductor compared with Supercon's previous T48 and A25 materials which were copper electroplated. This particular NbTi alloy was chosen because of its high current capacity at high magnetic fields that can be realized with a moderate addition of copper cladding. Area ratios of copper to superconductor of 0.69, 1.56, and 3.00 have been utilized.

The new fabrication process permits the addition of desired amounts of copper without the need for cabling.

A porous coil construction was utilized to permit helium gas and liquid to permeate the winding. The helium serves to bring the coil to temperature equilibrium and to provide a heat sink for losses encountered during charging.

Results of tests on partially submersed coils indicate that the helium gas is the primary heat sink at $4.2^\circ K$ operation. This heat sink is

significant since helium gas at 4.2°K has 100 times as much heat capacity per unit volume as copper.

Since the performance does not depend on liquid nucleate boiling there is no concern for vapor locking and some exposure of the coil above the liquid can be tolerated.

Turn-to-turn insulation was obtained by chemically oxidizing the copper cladding until it turned black.[1] This oxide layer is approximately 0.0001 in. thick and has a thermal conductivity much higher than organic coatings. The oxide is semiconducting at room temperature and insulating at liquid-helium temperatures. This semiconducting property could protect the coil from uncontrolled voltages if the magnet current were interrupted.

Layer-to-layer insulation was provided by a tightly woven fiberglass cloth 0.004 in. thick that was given higher strength by being impregnated with thinned, clear varnish. The presence of this varnish in the cloth was found not to have an adverse effect on the coil performance.

Table I.  Performance of Nb48%Ti coils at 4.2°K.

| Coil designation | | Ti-1 | Ti-2 | Ti-3 pair | Ti-4 pair | Ti-5 |
|---|---|---|---|---|---|---|
| Wire size ID/OD | (in.) | .015/.030 | .015/.030 | .010/.016 | .010/.016 | .010/.013 |
| Winding ID | (in.) | 5.0 | 1.5 | 1.8 | 1.5 | 0.44 |
| Winding OD | (in.) | 6.3 | 4.5 | 3.8 | 3.5 | 1.2 |
| Winding length | (in.) | 5.1 | 4.5 | 0.70 x 2 | 0.88 x 2 | 1.2 |
| Conductor length | (ft) | 4,480 | 5,430 | 3,640 | 3,480 | 513 |
| Max field on axis | (kG) | 33 | 67 | 45 | 55 | 58 |
| Max current | (A) | 168 | 117 | 68 | 70 | 74 |
| Short sample current | (A) | 220 | 115 | 68 | 70 | 70 |
| Max current at 1°K | (A) | 180 | --- | -- | >71 | -- |
| Packing factor | (%) | 16 | 19 | 27 | 27 | 38 |
| Av current density | (A/cm$^2$) | 24,000 | 20,000 | 37,000 | 38,000 | 55,000 |
| Heat transfer req'd for stability at max current and copper resistance ratio of 100 | (W/cm$^2$) | 0.6 | 0.3 | 0.9 | 0.9 | 2.3 |

Table II. Performance of Nb25%Zr coils at 4.2°K.

| Coil designation | | Zr-1 | Zr-2 | Zr-3 | Zr-4 | Zr-5 |
|---|---|---|---|---|---|---|
| Wire size ID/OD | (in.) | .010/.014 | .010/.014 | .010/.014 | .010/.013 | .010/.012 |
| Winding ID | (in.) | 2.1 | 2.1 | 2.6 | 2.2 | 2.2 |
| Winding OD | (in.) | 3.2 | 4.1 | 3.0 | 3.0 | 3.5 |
| Winding length | (in.) | 4.7 | 4.7 | 6.0 | 10.0 | 6.7 |
| Conductor length | (ft) | 7,620 | 13,120 | 3,180 | 13,500 | 16,020 |
| Max field on axis | (kG) | 46 | 53 | 16 | 35 | 40 |
| Max current | (A) | 46 | 37 | 50 | 38 | 28 |
| Short sample current | (A) | 50 | 37 | 75 | 62 | 60 |
| Max current at 1°K | (A) | 35 | -- | -- | 32 | 29 |
| Packing factor | (%) | 33 | 33 | 33 | 38 | 44 |
| Av current density | (A/cm$^2$) | 30,000 | 24,000 | 33,000 | 30,000 | 24,000 |
| Heat transfer req'd for stability at max current and copper resistance ratio of 100 | (W/cm$^2$) | 0.7 | 0.5 | 0.8 | 0.6 | 0.5 |

## COIL PERFORMANCE

The performance of several Nb48%Ti and Nb25%Zr coils is tabulated in Tables I and II. All of these coils are being utilized effectively in physical research, are self-protecting, and operate with high current densities.

The NbTi coils are superior to the NbZr coils in these respects:

1. The current capacity of the NbTi conductors for short samples and completed coils is significantly higher.

2. The NbTi conductor is dramatically more stable. The limit of this material to provide intense current densities within the present coil construction has yet to be determined. However, it should be noted that it does perform unstably when coated with organic insulation, as does NbZr. The current capacity of the tabulated NbZr coils is limited by the stabilization provided by the questionably-bonded copper electroplate.

## CURRENT STABILIZATION

Present analytical methods do not permit a determination of the current capacity of these coils. However, the heat transfer rates required for transient stability have been calculated for the condition that all of the conductor current is momentarily carried by the copper cladding. The heat produced is then absorbed by the gaseous and liquid helium within the winding.

The present NbTi coils have operated well beyond reasonable limits for this type of stability. Nevertheless this heat transfer requirement is given strong consideration in the design of a new coil.

There have been sufficient tests made with the NbTi and NbZr coils under widely varying conditions to add insight to their behavior.

### Thermal Environment

To produce an organic environment, coil Ti-1 was impregnated with alcohol and run at $4.2^{\circ}K$. The transition current thereby degenerated from 168 to 90A. This performance shows that good heat transfer to a heat sink is essential during the charging process.

### Training

After the alcohol-impregnated coil Ti-1 quenched at 90A, it could be charged to much higher currents at both $4.2^{\circ}K$ and $1^{\circ}K$ without transitioning. The coil had no training effects prior to being impregnated with the alcohol. It was not driven to transition with the subsequent higher currents because of possible damage which might be caused by the thermally-insulated environment.

### Charge Rate

The Ti-1 coil can be charged to its full current of 168 A in 30 sec with 6 V and to 100 A in 3 sec with 36 V while at $4.2^{\circ}K$.

When at $1^{\circ}K$, this coil was charged to 180 A in 7 sec with 24 V. Thus the $1^{\circ}K$ helium II is more effective in absorbing and dissipating the charging losses.

### Helium II Operation Near $1^{\circ}K$

Three NbZr coils were tested in helium II. The critical currents

corresponded to stability heat transfer rates from 0.4 to 0.5 $W/cm^2$. In these cases it appears that the coils transition when the heat transfer is inadequate to dissipate the heat resulting from all of the current being carried momentarily by the copper electroplate. It is assumed that the coils will be saturated with the superfluid helium.

The operation of NbTi coils Ti-1 and Ti-4 at currents of 180 A and 71 A respectively would require heat transfer rates of 0.7 and 0.9 $W/cm^2$ to recover from all of the current flowing in the copper cladding. It appears that either the current does not shift completely to the copper cladding, or that the shift is so rapid that the heat is absorbed by the copper and a thin film of helium that wets its surface.

This performance indicates that there is a fundamental difference in stability between the materials that may be explained by the superior bonding of the copper jacket to the NbTi.

## Electrical Shunting

Throughout the development of superconducting magnets, exceptional current capacity for all metal coils has been noted. The main disadvantage of these coils is that they are inconvenient to charge. In addition to providing a desirable thermal environment, it appeared at the time that the ability of these coils to shunt current was aiding their stability. Some of the tabulated coils have no insulation on the copper cladding other than natural oxidation. With shunting limited to between the turns, these coils can be charged to full current within 2 or 3 min.

Coil Ti-1 was wound in two different ways to test the effectiveness of controlled turn-to-turn current shunting.

On the first wind, the coil was strongly shunted turn-to-turn because of the bare copper cladding and also because of the presence of overlapping oxidized copper wafer shorting strips, which were placed across each layer. The coil required 30 min to charge to 175 A.

On the second wind, the copper cladding was fully oxidized to provide complete electrical insulation. The resulting coil could be charged to its maximum current of 168 A in 30 sec. The small decrease in current is not considered significant and might be explained by the coil being turned inside out during rewinding.

This coil performs as though it is short sample limited although the short sample current data for 40 kG is 220 A. It carried 175 A at $2^{\circ}K$ and 180 A at $1^{\circ}K$ in conformance with an expected increase in short sample current capacity at these lower temperatures.

The conclusion drawn from this experiment and similar ones is that interturn shunting is not an effective means of current stabilization. In fact, the heat produced by current shunting will cause premature transitions in thick windings unless they are charged very slowly.

## Copper Forms and Interleaving

Hard copper has been the preferred material for coil forms. However, there is no evidence that this shorted secondary stabilizes the coil. Brass was used for Ti-1 and stainless for Ti-2.

Some copper interleaving foils were used on Zr-1 and a 5 in. bore cable magnet. They block circulation, require space, are a short hazard, increase winding time, and are of no apparent value in the present coils. They may, however, assist in overcoming the deficiencies of a coil with an organic environment.

## Thickness of Fiberglass Insulation

Normally one layer of 0.004 in. thick fiberglass cloth is adequate for interlayer insulation. Coil Ti-1 used 2 layers of cloth on the second wind with no significant loss in performance.

## Coil Size

Larger coils require more copper for stabilization. In designing larger coils it is assumed that the copper cladding will be called upon to carry the design current momentarily. At present the copper is sized for heat transfer rates between 0.2 and 0.4 $W/cm^2$.

## COIL PROTECTION

Moderate-size coils of this construction are completely self-protecting. The current decays as a result of the increasing resistance within the winding during a transition, provided the voltage output of the power supply is limited. Protection of the coil depends on the current decaying before the wire is overheated at the transition origin. The stored energy of the coil is absorbed by the wire and the helium gas within the windings.

By comparing the heat capacity of the winding with the rate of heat being generated within the normal conductor from $10^\circ K$ to $300^\circ K$, the

following approximate expression for the maximum safe transition time
was determined:

$$T_s = 0.5 \times 10^{12} A^2/I^2,$$

where

$T_s$ = maximum safe transition time (sec),

A = area (cross section) of copper cladding (in.$^2$),

I = transition current (A).

For coil Ti-1, A = $5.3 \times 10^{-4}$ in.$^2$, I = 168 A, and a safe transition
time of 1 sec was determined.

The transition time constant can be estimated for this coil construction
by an empirical fit of an expression developed by Stekly[2] for the three-
dimensional propagation of a normal region:

$$t = 5 \times 10^4 A L^{1/4}/I^{3/4},$$

where

t = transition time constant (sec),

A = area (cross section) of copper cladding (in.$^2$),

L = inductance (H),

I = transition current (A) .

This expression was fitted to the largest coil Ti-1, where
A = $5.3 \times 10^{-4}$ in.$^2$, L = 1 H, I = 168 A, and a transition time constant
of 0.5 sec was measured. The resulting equation is in good agreement with
the measured transition time constants of the other coils when their copper
forms are compared with the brass form of coil Ti-1. The time constants

of the coils with copper forms are approximately half of the value determined by the above equation.

## Coil Form Material

High-conductivity coil forms can absorb much of the stored coil energy if the time constant $L/R$ of the form is long compared with the transition time constant of the coil. Had the form for the Ti-1 coil been made of copper, the time constants would have been approximately equal.

## Propagation of the Normal Region

The most effective way in which these coils are protected is that a normal region will propagate very rapidly from the warm helium gas expanding away from the transition origin. This rapid propagation results in the stored energy being distributed over a large fraction of the volume.

## Semiconducting Shunts

Coils significantly larger than Ti-1 will not be self-protecting when operating at high current density. Semiconducting shunts consisting of oxidized copper wafers placed in contact with the oxidized copper-clad conductors offer one means of protecting these coils. The shunts will detour an increasing fraction of the current as the region warms up and the semi-conducting property of the copper oxide is restored.

When the turns are not fully insulated, sections of the coil away from the transition origin will be driven normal by transformer action during the rapid field decrease. By these mechanisms the stored energy can be dispersed throughout the coil.

External dumping of the energy depends on electronic circuitry and may require excessive voltages.

## 5 in. BORE, 40 kG CABLE COIL

One magnet utilizing 6,000 ft of Nb48%Ti cable and 6,000 ft of Nb25%Zr cable was constructed.[3] The ratio of copper electroplate to superconductor was 0.44. The coil was strongly shunted turn-to-turn and required 20 min to charge. Although the shunting did not appear to increase the current capacity, a transition could be averted by detecting a resistive voltage drop across the coil. The performance of this coil does not compare well with the later Nb48%Ti coils that have more copper metallurgically bonded to the superconductor.

At present, cables are being considered only for special applications such as pulsed magnets.

## CONCLUDING REMARKS

The present coil construction utilizes many of the principles of stable coil design and permits the attainment of current densities far in excess of the stable type design that depends on nucleate boiling heat transfer rates of approximately 0.4 W/cm$^2$. If necessary, the present coils can be operated in helium II where this heat transfer can be realized for momentary surges of current in the substrate.

These coils can be just as safe and reliable as stable coils. In large coils or critical applications the magnets need not be deliberately transitioned, so that the detection of the onset of normality is not required.

The present construction has permitted economic and performance advantages not otherwise available.

## ACKNOWLEDGMENTS

## REFERENCES

1.    R. E. Hintz and C. Laverick, "An Inorganically Insulated Super-conducting Solenoid for Operation at $1^{\circ}K$, " paper presented at Stanford International Symposium on Magnet Technology, Stanford, California, 1965.

2.    Z. J. J. Stekly, "Theoretical and Experimental Study of an Unprotected Superconducting Coil Going Normal, " in: International Advances in Cryogenic Engineering (Plenum Press, New York, 1962), p. 585.

3.    R. E. Hintz, "Inorganic Insulated NbZr and NbTi Solenoids, " paper presented at National Superconductivity Information Meeting, Brookhaven National Laboratory, New York, November 1966.
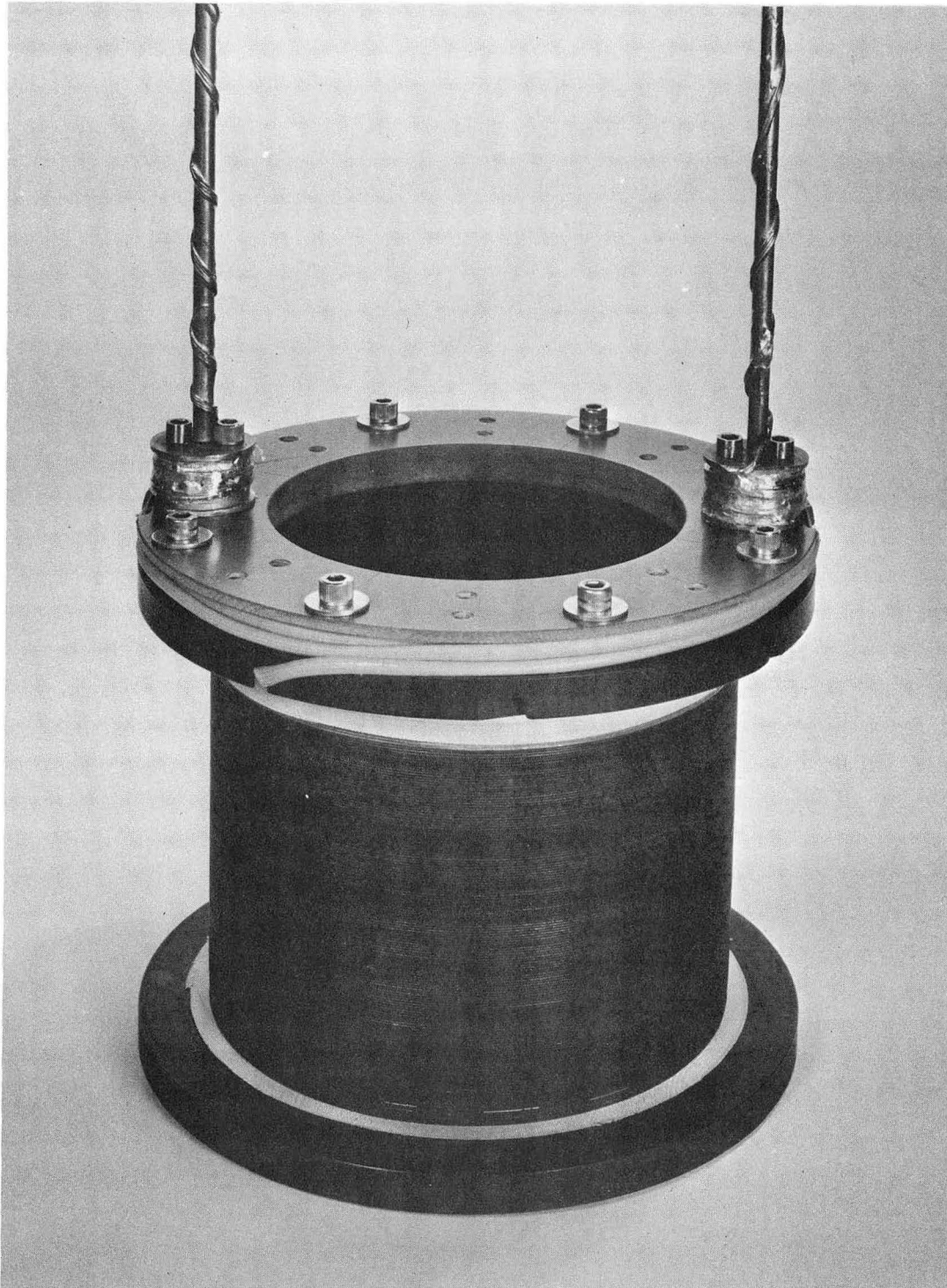
CBB 675-2819

Fig. 1.  Coil Ti-1.  5 in. bore, 33 kG, 24,000 A/cm$^2$.
Winding will be increased from 6.3 to 8.0 in. OD.
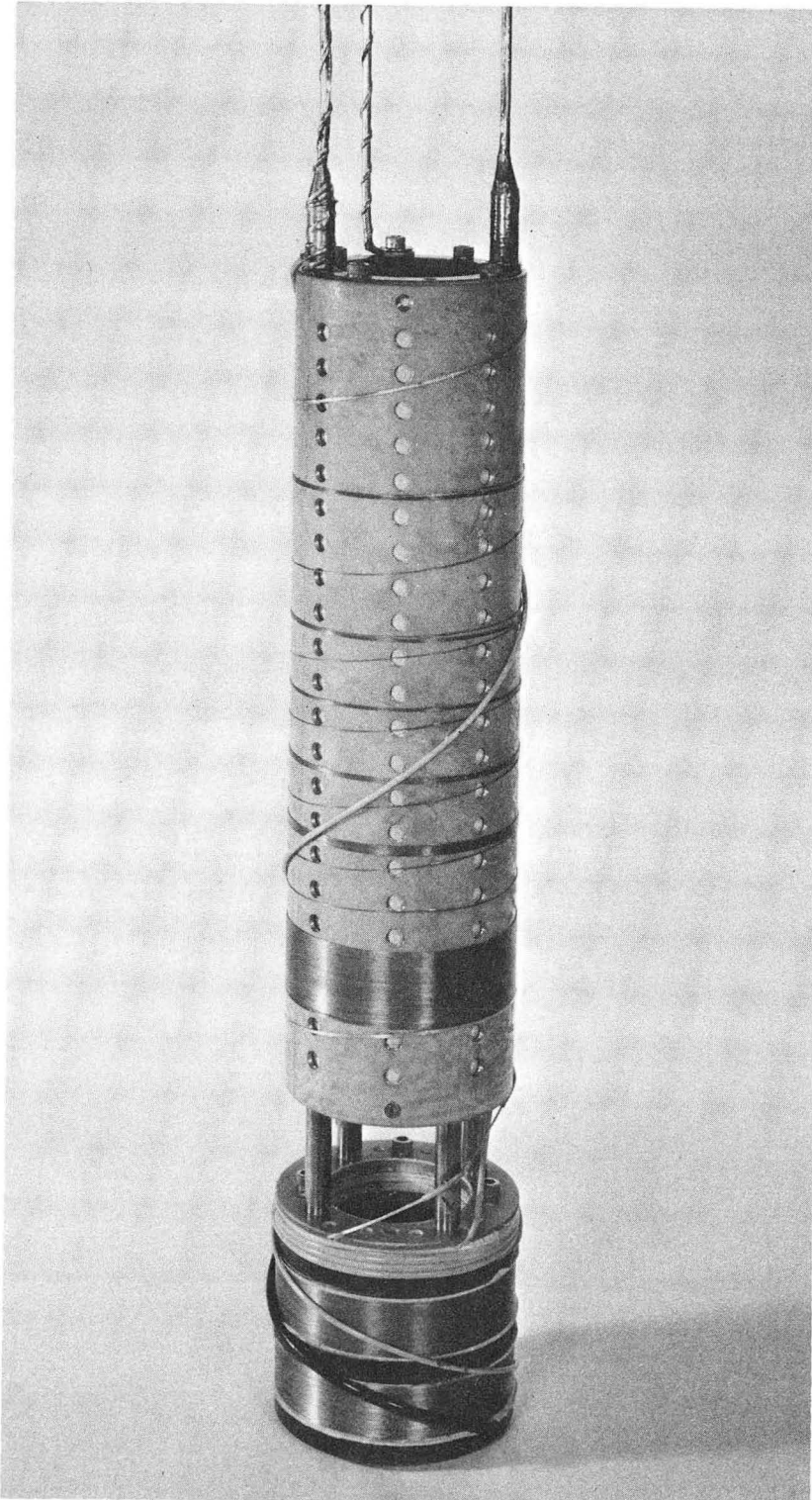
CBB 676-3451

Fig. 2. Coil system. Coil Ti-4 on bottom.
Coil Zr-4 inside compensating winding.
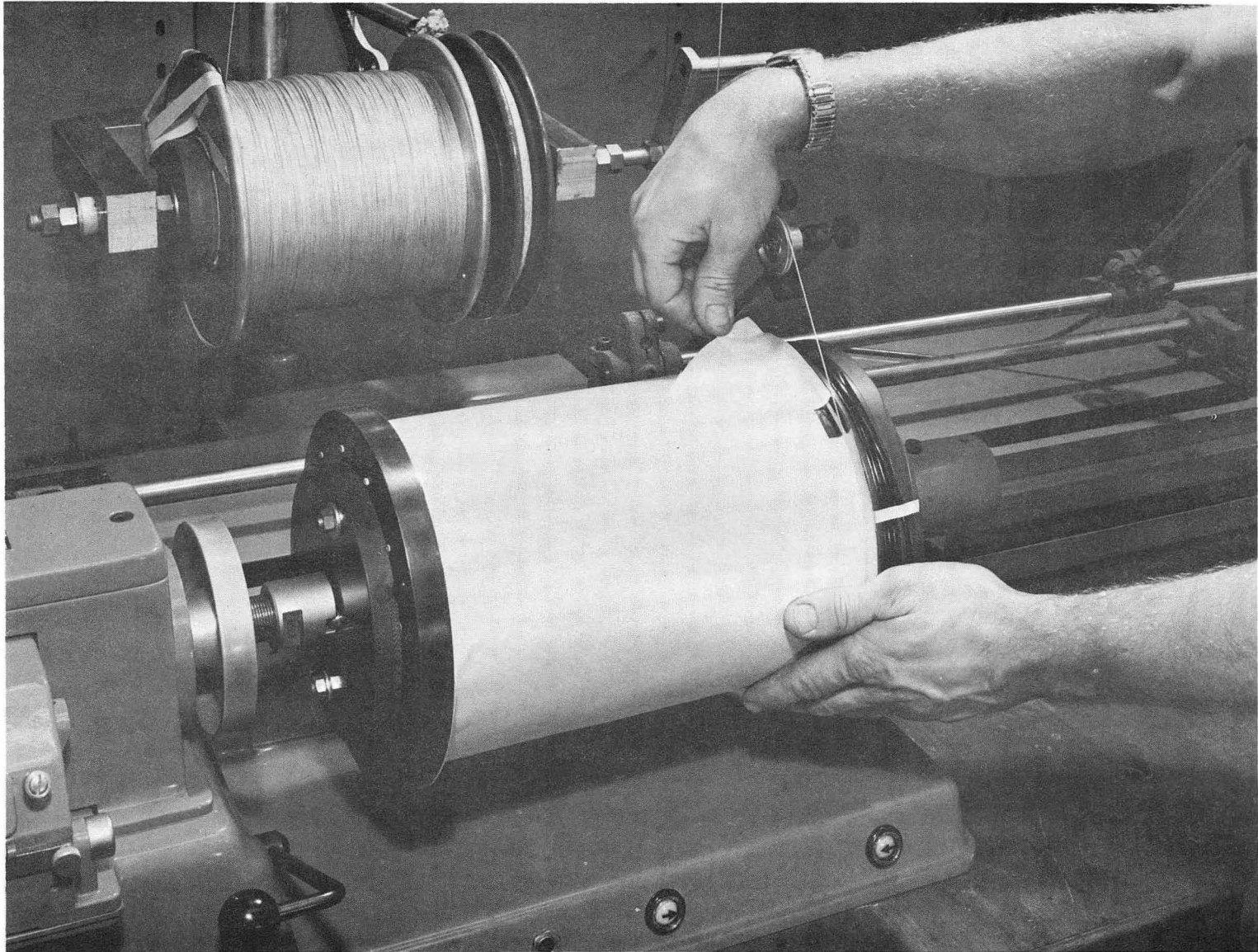
Chem 4139

Fig. 3. 5 in. cable magnet. Fiberglass installation.
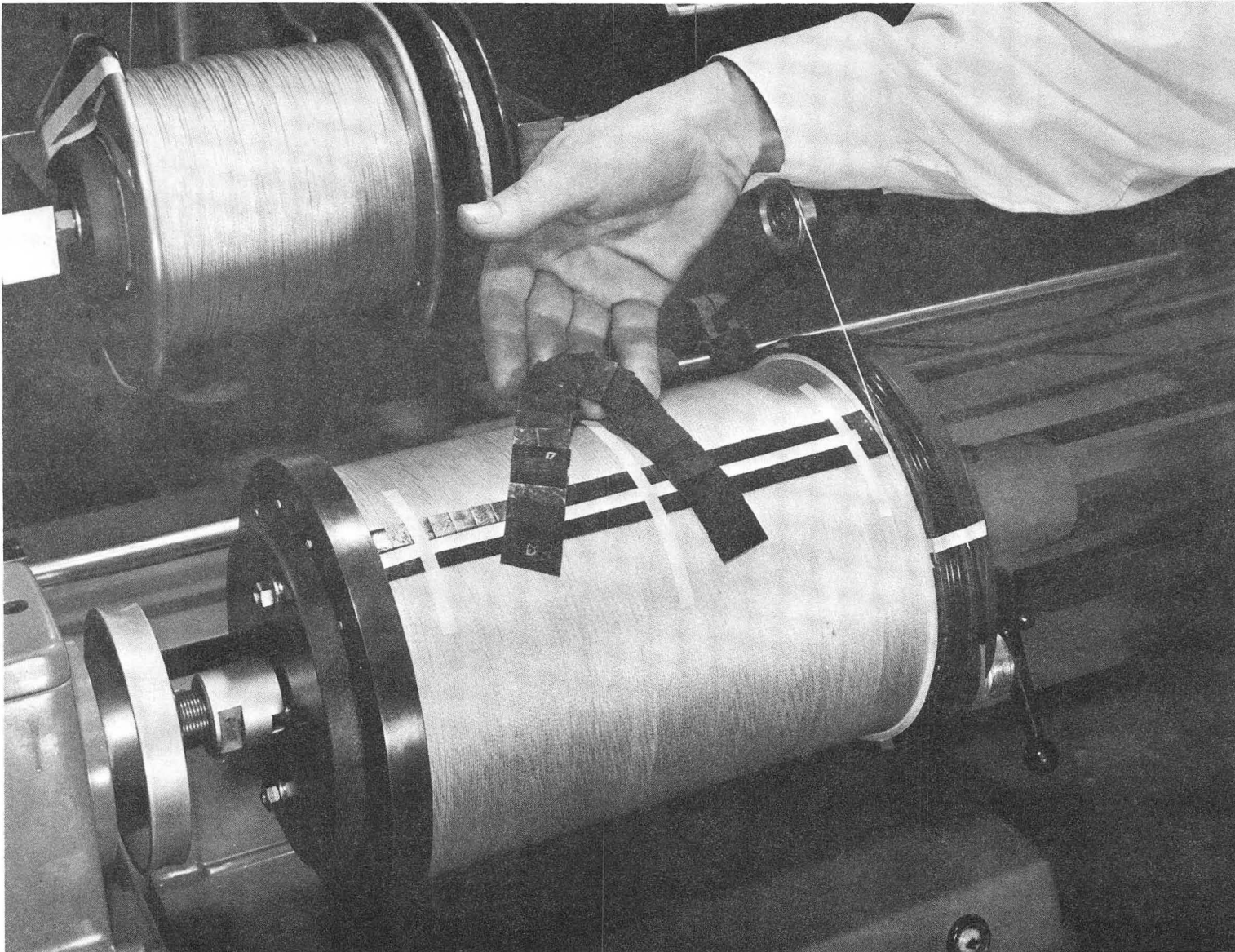
Chem 4138

Fig. 4. 5 in. cable magnet. Oxidized copper wafer
shunting strips.
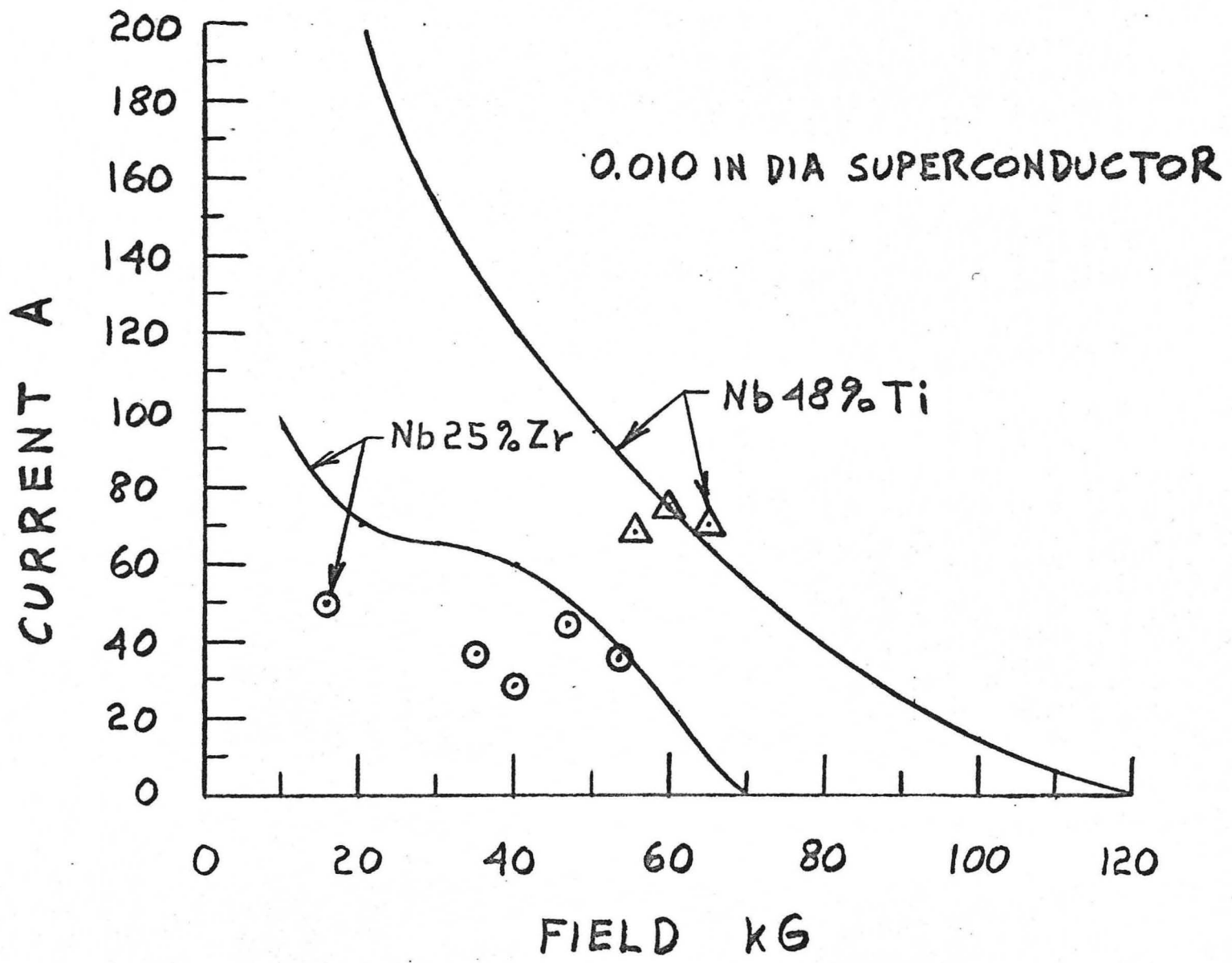
FIG. 5. COIL PERFORMANCE VS. SHORT SAMPLE DATA