DRAFT

CONF-791102--148

ADVANCED DESIGNS FOR HIGHLY STABLE SUPERCONDUCTOR SYSTEMS*

J. W. Lue and J. R. Miller**

Summary

Experimental evidence is mounting for enhanced stability against pulsed heat loads in cable-in-conduit conductors brought about by transient pressure waves in helium. It has been suggested that this enhancement derives from improved heat transfer caused by pressure induced flow and from extra heat absorption capability due to the thermodynamic path followed by helium in the course of pressure rise and release. We have conceived a basic conductor design to take advantage of these phenomena yet avoiding the difficulties encountered in the force-cooled conductor presently under development. We discuss the design in terms of manufacturability, performance, and applicability in large fusion magnets. A few small scale test conductors have been constructed. Preliminary test results on the performance of one of them is included. Possible variations offered by the flexibility of the basic design is also discussed.

Introduction

High current density stable conductor is always a desirable thing to have for a superconducting magnet. As the fusion reactor design progresses, this desirability becomes more and more apparent. Investigation on the stability of superconductors and superconducting magnets

*Research sponsored by the Department of Energy under contract W-7406-eng-26 with Union Carbide Corporation.

**Oak Ridge National Laboratory, Oak Ridge, TN 37830.

will put this under names in title on the mats has been going on for years. Fairly good analysis of what perturbation a conductor can take has been achieved, though knowledge of the quenching mechanisms in a superconducting magnet is still very incomplete. It is, however, generally agreed that the most detrimental source of trouble for a superconducting magnet is a sudden transient heat generation caused by conductor motion, flux jumping, or other unknown reasons.

In the course of stability investigations[1-3] of cable-in-conduit conductors for force-cooled superconducting magnets, we have found several very attractive features of this type of conductors: (1) because of the large surface area it possesses, it does not require a high heat coefficient, and therefore does not require high helium flow with high pumping loss; (2) conductive transient heat transfer[4,5] is very helpful for low heat input as can be seen from the considerable delay between the start of heat input and the onset of resistive voltage on the conductor; (3) there is a pressure surge in helium after a transient heat load which can drive the subcooled helium into supercritical state such that no vapor blanket is formed on the surface of the conductor; (4) the release of the built-up pressure induces a transient local flow which enhances the heat transfer coefficient; and (5) there is also an extra heat absorption capability due to the thermodynamic path followed by helium in the course of pressure rise and release.

Using cable-in-conduit conductors in forcecooled mode, such as the one proposed by Westinghouse for LCP[6] has, however, its drawbacks: (1) the conductor requires manufacturing technique that is problematic at present and is further complicated by possible ill effects on the stainless steel sheath in reacting Nb_3Sn; (2) the plumbing design is more complicated; (3) it is hard to protect the coil in case of quench. This is particularly so due to the very low copper fraction in the conductor; and (4) there is still a substantial pumping loss to pay. This will be aggravated if there is a constant heat load to the magnet such as the EBT[7] operation.

An advanced design for highly stable superconductor systems has been undertaken that takes advantage of the attractive features of the cable-in-conduit type conductors yet avoiding the difficulties encountered in the force-cooled conductor presently under development.

Proposed Conductor Configuration

A pool-cooled conductor which uses a relatively long channel to contain helium for transient cooling of the superconductor has been conceived. It consists of cabled (or braided) superconducting strands enclosed in a substrate/jacket which is dispersely perforated. There is a substrate strip spirally wrapped on the superconducting cable. The whole conductor is to be wound into a magnet with conventional inter-winding cooling. We shall use a 15 kA, 12 T Nb_3Sn conductor as the model for construction process description. It is shown in Fig. 1.

The superconducting cable is made of $6 \times 3^3 \times 1.05$ mm transposed strands cabled around a 3-mm stainless steel core. The latter serves as a strengthening member of the conductor. The cable is compacted to a diameter of 15 mm leaving a void of about 17% for helium. A 10-mm wide, 1-mm thick copper strip is spirally wrapped on the cable, covering half of its surface. When the substrate/jacket is applied, there is additional helium space formed between the strips. The total void inside the 17-mm diameter cable space is about 24%. The heat treatment for forming Nb_3Sn can be done before or after the copper strip is applied. By doing it after, care should be taken to prevent the strip from fusing to the cable. But it has the advantage of no physical contact and less handling on reacted Nb_3Sn cable, and the softened copper strip will give and take the compressive load when the substrate/jacket is applied.

The copper substrate/jacket is formed by two rectangular strips with half-circle rolled on them to fit the cable. The two halves are brought onto the cable and soldered to one another. An interior cooling channel is formed along the cable. Helium communication with the pool is provided by the 5-mm holes at the corners of the substrate/jacket. They are dispersely spaced at 2 m apart. For a 1:1 Cu to superconductor ratio in the cable, the overall copper-to-noncopper (superconductor and structural element) ratio is 4.8:1. At the design current of 15 kA, the current density over the whole conductor (including interior helium space) is 3000 A/cm^2. Conventional insulation such as spirally wrapped fiberglass and G-10 strips can be used in the coil winding. The winding void is expected to provide a helium pool with as much space as the conductor interior void.

Design Rationale

Current switches to low resitivity substrates when a superconductor goes normal. The resulting joule heating and temperature excursion depends on the amount of substrates used. Thus reasonable amount of substrates is needed for both conductor stabilization and coil protection. The use of copper substrate/jacket provides the necessary low resistivity substrate. It is well cooled in pools both inside and outside. Although there is only pressure contact between cable and strip, and between strip and substrate/jacket, no difficulties are anticipated for the current to transfer between the superconducting cable and the substrates. It has been shown experimentally that a sizable resistive barrier between superconducting composite and additional substrate will not degrade conductor stability compared to uniform distribution appreciably. The substrate/jacket also serves as thermal and magnetic shield for the superconducting cable. Steady outside heat load will mostly be absorbed and conducted away by the substrate/jacket before it reaches the cable. Transient magnetic pulse, such as that induced by the plasma quenching will be greatly shielded by the substrate/jacket. The model conductor is estimated to have a magnetic time constant of about 25 ms. No pulse field can reach the superconductor faster than this. Granted, this shielding function has to be weighted against higher eddy current losses in the substrate.

The choice of 2-m spacing between helium access holes is based on limited experimental data.[1-3] It is far enough to take at least some advantage of the pressure surge, induced flow and thus enhanced heat transfer and heat absorption capability effects following a transient heat load. Much too far a spacing may cause undesirably long delay in replenishing helium after a transient. More work is needed to determine whether there is an optimum spacing for a particular condition.

The purpose of compacting the cable and using copper strip spirally wrapped on the cable instead of having uniform looser cable is threefold: compacting the cable reduces the probability of wire motion which is of concern in using cable; additional helium space between the cable and substrate/jacket formed a single large internal cooling channel which eases helium replenishment and reduces danger of vapor blockage; and the stand-off provided by the strip protects the cable from damage when applying substrate/jacket.

The stainless steel core serves as a strengthening member of the conductor only. Additional supporting structure will be needed for the magnet. Various types of structure can be used. A possible attractive approach is a box-type structure. Every box structure contains several turns and several layers to reduce load accumulation.

Test Conductors

Several test conductors based on the proposed conductor configuration have been made. Figure 2 shows a photomicrograph of the cross-section of a conductor. It consists of 6 x 4 x 3 x 0.574 mm NbTi strands cabled around a 4 x 3 x 0.574 mm copper core. All strands are bare, there is no insulation nor solder. Inside each of the 4 x 3 subcable there is an insulated manganin heating wire. To maintain the heater insulation integrity only light compaction was applied on the cable. A 6.0 mm x 0.56 mm copper strip was spirally wrapped on the cable. It was then slid inside a copper tubing. A final swaging was applied to bring the tubing onto the strip. The outside diameter of the substrate/jacket is 10.5 mm.

A 4.5-m long conductor was bifilarly wound on a 220 mm diameter form and hanged at the end of a pair of 15-kA vapor-cooled leads as shown in Fig. 3. In this setup, it will be tested first in pressurized and force-cooled mode. Additional access holes will then be opened along the conductor to check the differences in performance at different access hole spacing.

Possible Variations of this Conductor Concept

Special attention has been given to the manufacturability of the proposed conductor design. This concept is quite flexible that variations can be easily adapted.

- Although round cable is used as the model, rectangular cable or braid may be desirable. This can make compaction easier and simplify substrate/jacket fabrication. Rectangular conductor shape is the choice for coil winding.
- Different techniques can be used in applying the substrate/jacket. The model example is suitable for larger conductors. For smaller conductor and thinner substrate/jacket, wrapping with overlaps for soldering can be used. The spiral strip and the substrate/jacket can also be replaced by aluminum.
- With proper cryostats the coil can be cooled by flowing supercritical helium through the winding or in a superfluid helium pool. These two forms of coolant are necessary only if vapor trapping in the cable occurs for atmospheric pressure helium or if high field operation is required.
- Without helium access holes along the conductor, it can be operated in forced-flow mode. This conductor differs from the LCP-Westinghouse force-cooled conductor[6] in that it has a higher fraction of low-resistivity substrate. Thus it will be more stable and much easier to protect in case of quench. It has easier jacketing task to tackle. It has a large internal cooling channel on the periphery of the cable, an idea that has been suggested by others.[9] Lower pumping power is required for a given mass flow rate, though the helium velocity in the cable interstices will be lower. It has, however, been shown that high imposed flow is not necessary for cable-in-conduit conductors.[2,3] In this force-cooled mode, thicker strip or grooves on the inside surface of substrate/jacket may be needed to make up the helium pool fraction loss.

- A larger variation of the above design is to use a dual cooling system for the conductor. The superconducting cable (with limited amount of copper) is enclosed in a thin-wall jacket and is cooled by low flow supercritical helium. Substrate in cable or multi-grooved form is added on the outside of the jacket. This is cooled by a helium pool through the coil winding. When the superconductor goes normal, current switches to the outside substrate. Most of the joule heating is taken away by the helium pool. As soon as the internal supercritical helium cools the superconductor below its critical temperature, current will switch back to the superconductor. Since no high mass flow is necessary for the superconducting cable, the additional cooling system may not be as complicated as one thought. More tests on this concept are, however, needed.

References

1. J. W. Lue, J. R. Miller, and L. Dresner, "Vapor Locking as a Limitation to the Stability of Composite Conductors Cooled by Boiling Helium," *Advances in Cryogenic Engineering* 23, 226 (1979) Plenum Press, New York.

2. J. R. Miller, J. W. Lue, S. S. Shen, and J. C. Lottin, "Measurements of Stability of Cabled Superconductors Cooled by Flowing Supercritical Helium," *IEEE Transactions on Magnetics*, MAG-15, No. 1, 351 (1979).

3. J. W. Lue, J. R. Miller, and L. Dresner, "Stability of Cable-in-Conduit Conductors," to be published in *Journal of Applied Physics*, January (1980).

4. W. G. Steward, "Transient Helium Heat Transfer. Phase I — Static Coolant," *Int. J. Heat & Mass Transfer* 21, 863–74 (1978).

5. C. Schmidt, "Transient Heat Transfer to Liquid Helium and Temperature Measurement with a Response Time in the Microsecond Region," *Appl. Phys. Lett.*, 32 (12) 827–28 (15 June 1978).

6. J. W. H. Chi, J. H. Murphy, and C. K. Jones, "Selection of a Cryostabilized Nb_3Sn conductor Cooling System for the Large Coil Program," *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research*, 940 (1977).

7. N. A. Uckan, et al, "Physics and Engineering Aspects of the EBT Reactor," *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research*, 614 (1977).

8. J. R. Miller, L. Dresner, and J. W. Lue, "Investigation of Current Transfer in Built-up Superconductors," *Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research*, 1282 (1977).

9. M. O. Hoenig, A. G. Montgomery, S. J. Waldman, "Cryostability in Force-Cooled Superconducting Cables" *IEEE Transactions on Magnetics*, MAG-15, No. 1, 792 (1979).

ORNL DWG 79-2132 FED

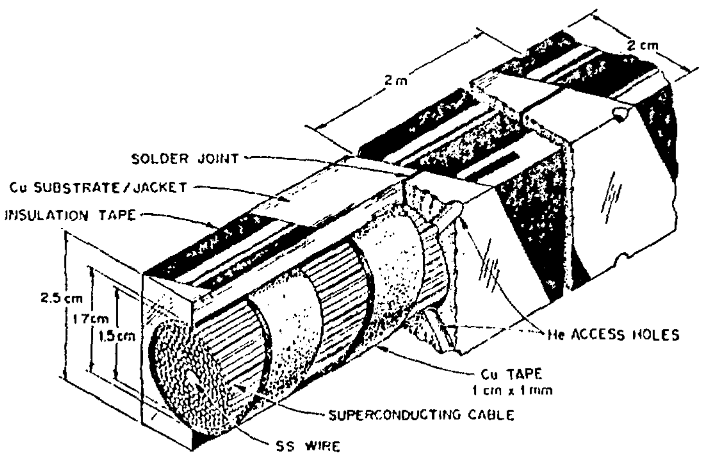


Fig. 1 Model Superconductor Configuration

glossy for poster — 2, View graphs — 2

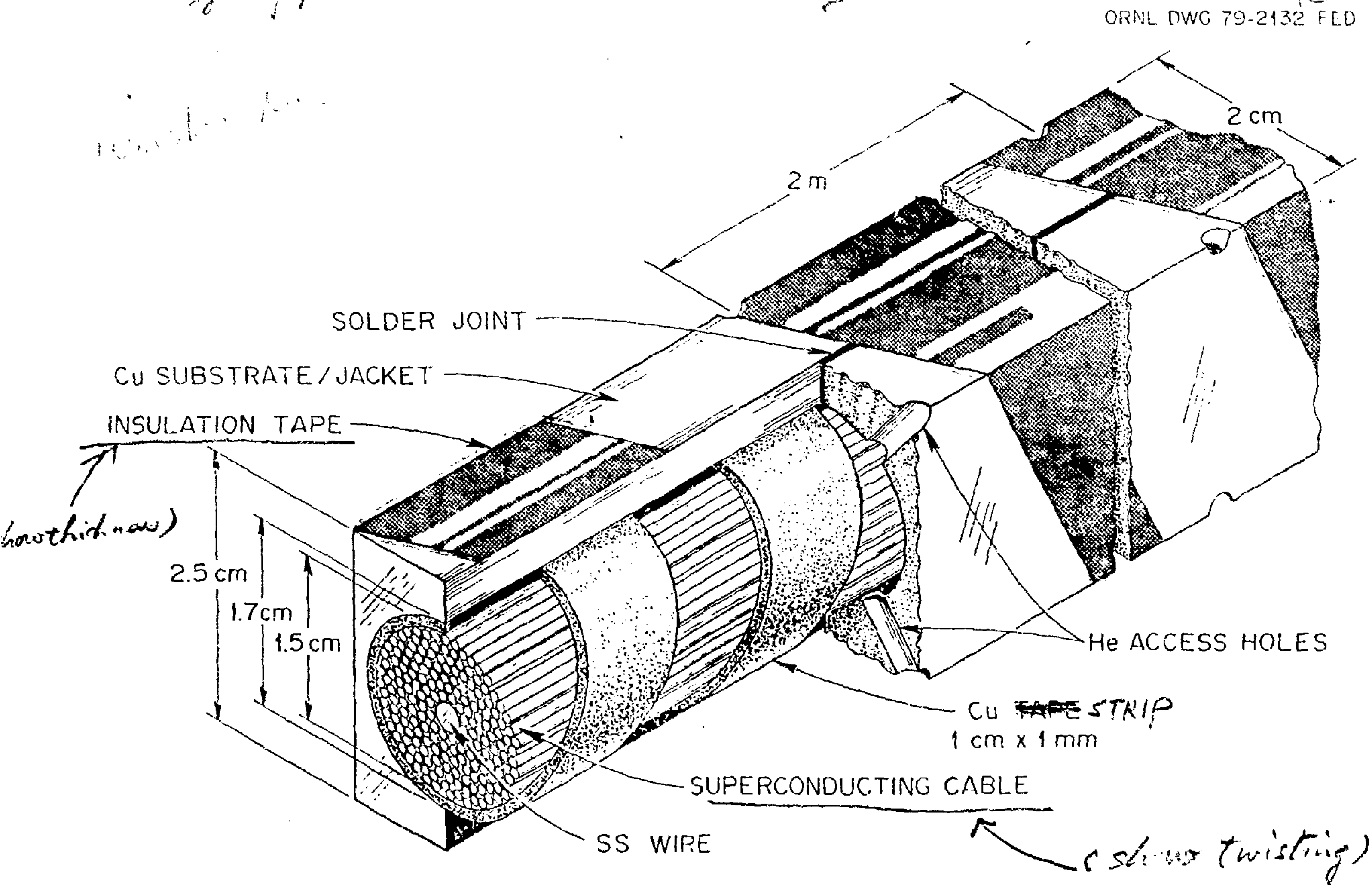
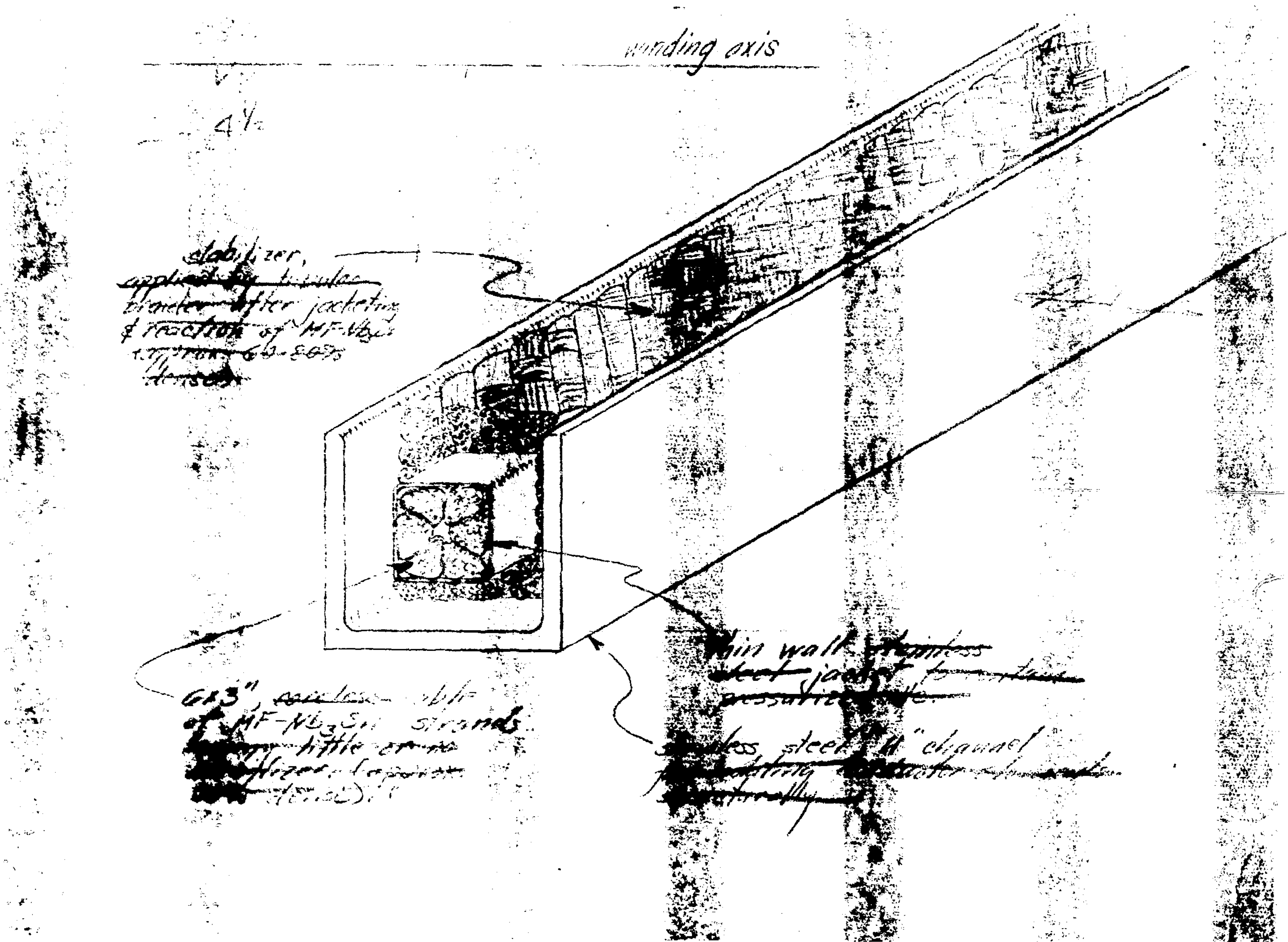


Figure 1. Model Superconductor with Pressure Wave Enhanced Stability



winding axis
4½
stabilizer,
after jacketing
thin wall
jacket
steel "U" channel
strands