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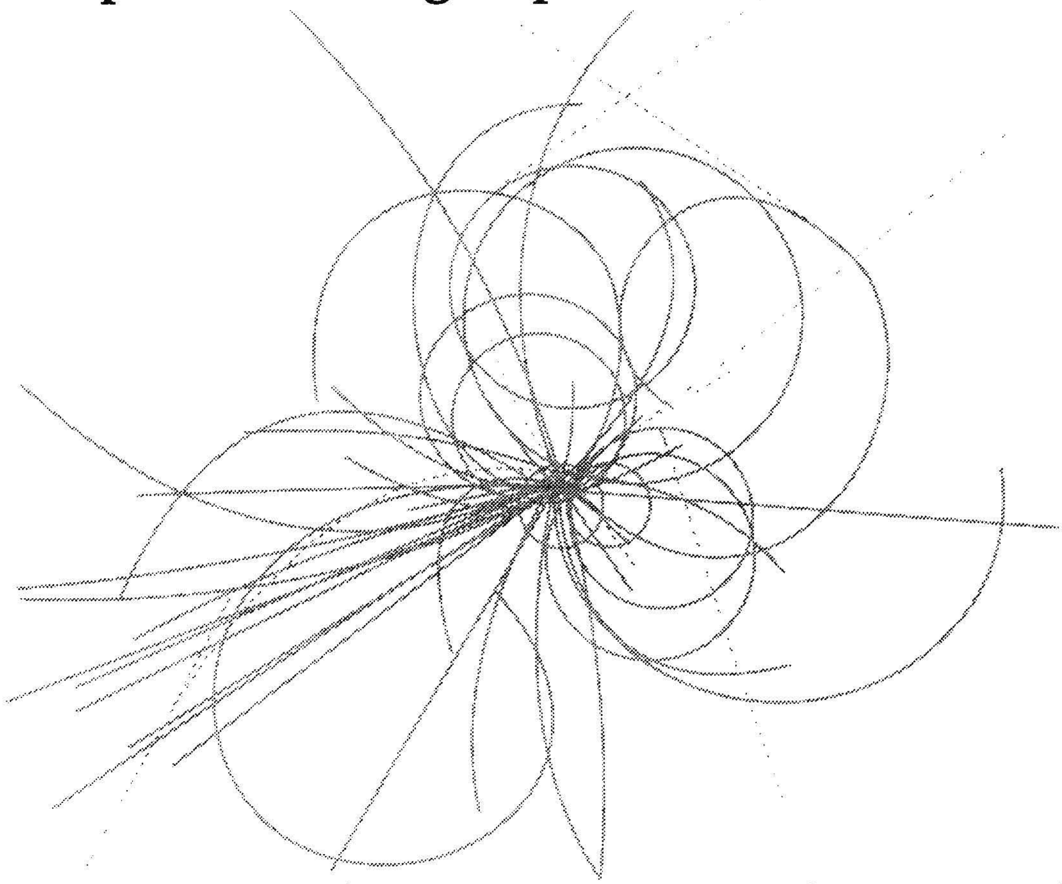

Thermal Optimum Analyses and Mechanical Design of 10-kA, Vapor-Cooled Power Leads for SSC Superconducting Magnet Tests at MTL

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August 1992

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THERMAL OPTIMUM ANALYSES AND MECHANICAL DESIGN OF 10-kA, VAPOR-COOLED POWER LEADS FOR SSC SUPERCONDUCTING MAGNET TESTS AT MTL

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Abstract–The spiral-fin, 10-kA, helium vapor-cooled power leads have been designed for Superconducting Super Collider superconducting magnet tests at the Magnet Test Laboratory. In order to thermally optimize the parameters of the power leads, the lead diameters—which minimize the Carnot work for several different lengths, two different fin geometries, and two RRR values of the lead materials—were determined. The cryogenic refrigeration and liquefaction loads for supporting the leads have also been calculated. The optimum operational condition with different currents is discussed. An improved mechanical design of the 10-kA power leads was undertaken, with careful consideration of the cryogenic and mechanical performance. In the design, a new thermal barrier device to reduce heat conduction from the vacuum and gas seal area was employed. Therefore, the electric insulation assembly, which isolates the ground potential parts of the lead from the high-power parts, was moved into a warm region in order to prevent vacuum and helium leakage in the O-ring seals due to transient cold temperature. The instrumentation for testing the power leads is also discussed.

I. INTRODUCTION

With ten cryogenic test stands, the Magnet Test Laboratory (MTL) is capable of testing up to 30 dipoles (each dipole 15 m in length) and 5 quadrupoles (each quadrupole 5 m in length) per month. For further improvements and analyses of SSC magnet performance, there will be two R&D test stands for extensively instrumented magnets and a three-magnet string test facility.

A pair of vapor-cooled power leads will be installed into the feed can of each cryogenic test stand. Energizing these large-scale superconducting magnets is accomplished through the vapor-cooled power leads, which communicate between the magnets and a power source. The heat entering the low-temperature zone by Joule heating and solid conduction through the power leads not only influences LHe consumption and the temperature of single-phase, supercritical He, but it also affects the safety of the magnet operation. Considering the busy and strenuous test tasks scheduled for the MTL, efficiency, stability, reliability, and demountability become the highest priorities in the design of the vapor-cooled power leads.

In order to increase the heat-exchange surface of the leads, various approaches are employed by making different current carriers in the cold-vapor flowing channels. Those are: (1) braided leads, (2) leads made of strips collected into a packet, (3) leads made of wires and tubes, (4) leads with spiral-fin current carrier, and (5) leads made of porous materials. Each structure has its own unique advantages and shortages. The power lead designs of Fermilab, BNL, DESY, CERN, LBL, and Oak Ridge [1–5] were studied with regard to use in MTL. The structure of the spiral-fin, vapor-cooled power lead was chosen for MTL. It was also learned that there are considerable differences in the design parameters of the same type structure of the spiral-fin leads. For instance, one of the Fermilab 10-kA power leads has a 130-cm-long, spiral-finned section with a core diameter of 2.54 cm [1], and the BNL 10-kA design is only 46 cm in length with a diameter of 1.4 cm [2].

After reviewing these designs, it becomes apparent that studies were required to determine the optimum design parameters for the MTL power lead. An extensive thermal optimization was accomplished to meet the constraints: maximum heat flux of 7.9 W and maximum single-phase He flow rate of 0.07 g/s per 1,000 A. Then, the optimum dimensions were searched in order to minimize the refrigeration and liquefaction loads to the cryogenic system. Two geometries of the spiral fins and two RRR values (40 and 100) of fin materials were used in the analyses. These calculations provide direction for a power lead design in the selection of these important dimensions.

Several important improvements were made in the mechanical design. According to our experience, during normal operation of vapor-cooled power leads (VCPL), transient conditions can occur that result in extremely cold temperatures at the electric power input connector, the vacuum seal area, and the transition area from the high power to ground. In the design, a new thermal barrier device to reduce heat conduction from the vacuum and gas seal area was employed. The electric insulation assembly, which isolates the ground-potential parts of the lead from the high-power parts, was moved into a warm region in order to prevent vacuum and helium leakage in the O-ring seals due to low temperature.

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II. RESULTS OF THERMAL OPTIMIZATION

In order to determine the optimum design parameters for our particular cases, a numerical model was employed that is described in Schiesser [6], Demko [7], and Shu [8]. The thermal behaviour of the leads was modeled using one dimensional transient energy balances for the helium and the lead as given by Eqs. (1) and (2).

$$\frac{\partial}{\partial t}(\rho_c e_c dv) = \frac{\partial}{\partial x}\left(kA\frac{\partial T_c}{\partial x}\right)dx + hP(T_c - T_v)\,dx + Q_j \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho e_v dv) = \dot{m}\frac{\partial i_v}{\partial s}\,ds + hP(T_v - T_c)\,dx, \qquad (2)$$

The subscripts c and v indicate whether the variable applies to the conductor or the helium respectively. The variables T and ρ are the temperature and density, i is the enthalpy, e is the internal energy, h represents the heat exchange by convection, A is the lead cross section, and P is the available surface area for heat transfer per unit length along the lead. The quantities dv, dx, and ds represent the differential volume, distance along the lead axis, and distance along the helium flow path. Q_j is the resistive heating of the lead. The heat transfer coefficient is given by the following for two different flow regimes:

$$Nu_{Re<2000} = 6.6 \qquad (3)$$

$$Nu_{Re>2000} = 0.0259 \times Re^{0.8} \times Pr^{0.4} \times \left(\frac{T_v}{T_c}\right)^{0.716} \qquad (4)$$

The fins were assumed to be isothermal in the radial direction. The mass flow rate of helium was determined assuming no heat transfer to the environment at 300 K. At the top end of the lead, heat transfer coefficient to the environment of 2.2 W/cm^2K, based on the lead core area, was used.

Most of the previous work to optimize dimensions of leads are based on the assumption that the boil-off from the helium cryostat would be used to cool the warm end of the lead. The Carnot work, which represents the minimum work required by the cryogenic system supplying the liquid helium and the 4-K refrigeration, is more appropriate for applications such as the SSC, where supercritical helium will be used to cool the lead. Several lead lengths were analyzed by varying the diameter to determine which diameter provided the minimum Carnot work defined by the following equation:

$$W_{Carnot} = \dot{m}_{He}\Delta h_{liq} + \left(\frac{T_h - T_c}{T_c}\right)\dot{Q}_c \qquad (5)$$

The first term on the right-hand side represents the ideal work required to liquefy the helium vapor from $T_h = 300$ K and 1 atm to $T_c = 4.2$ K and 4 atm. For these states the ideal liquefaction work is 7011 J/g. The second term is the ideal refrigeration required to remove the heat conducted by the lead to the 4-K level.

Fig. 1 shows two cases of the geometries of the spiral fins used in the analyses. Some results for the allowable lead dimensions for these particular cases are provided in Figs. 2–4. Fig. 2 shows a comparison between the two fin geometries described in Fig. 1. The heat flux limit of 7.9 W is nearly the same for the two geometries. The diameters that minimize the Carnot work are smaller for the new geometry (*i.e.*, Case B) at a given length. In any case, the change in fin geometry did not significantly affect the design space.

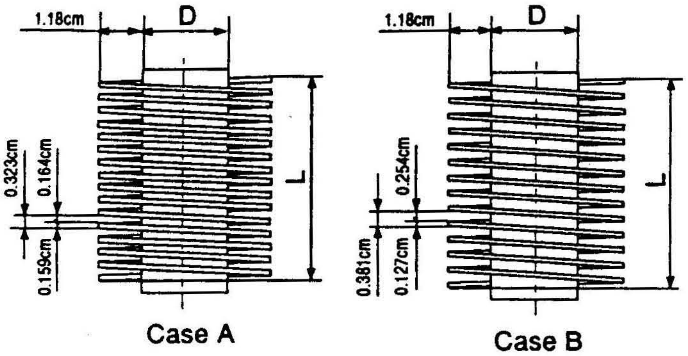

Fig. 1. Dimensions of two spiral fins used in the thermal analyses.

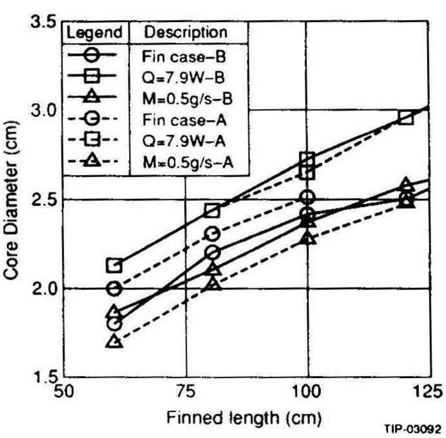

Fig. 2. Comparisons of the effects of fin geometries on the dimensions of a 10-kA VCPL with RRR = 40.

The lead dimensions that minimize the cryogenic system work, or satisfy prescribed heat flux or mass flow limit constraints, are shown in Figs. 3 and 4 for copper with RRR = 40 and 100, respectively, and the case B fin geometry. In both cases the minimum Carnot work line falls close to the line, indicating a heat flux limit of 1W.

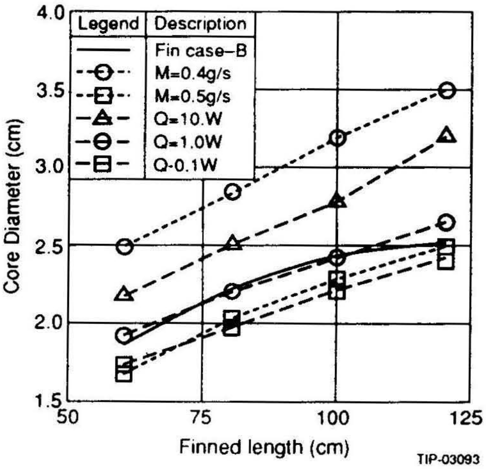

Fig. 3. Optimum 10-kA power lead dimensions with RRR = 40 and case B fins, respectively, for different flow rate limits, heat flux limits, and minimum cryogenic system work.

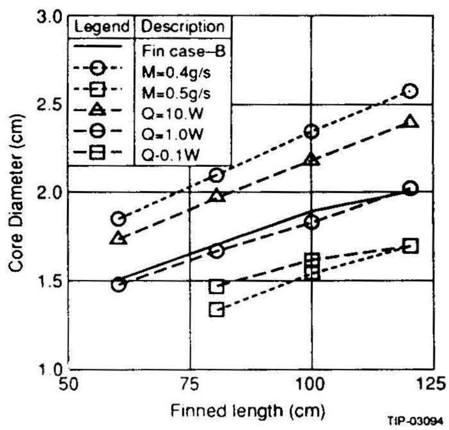

Fig. 4. Optimum 10-kA power lead dimensions with RRR = 100 and case B fins, respectively, for different flow rate limits, heat flux limits, and minimum cryogenic system work.

III. MECHANICAL DESIGN

A. General Description

The vapor-cooled power lead (Fig. 5) consists of a finned copper conductor assembly (Fig. 6) that has a copper power head brazed onto its warm end and superconducting cable soldered into its cold end. This assembly fits inside of a "folded" G-10 insulating tube assembly, which in turn fits into the feed can mounting assembly (Fig. 7). The copper fin of the power lead is brazed onto the copper power lead bar in a spiral with a pitch of 3.81 mm, as case B in Fig. 1. After brazing on the fin, the assembly can be machined to its final fin diameter of 46.02 mm. The stainless steel outer tube is brazed onto the copper power head. The assembled power lead is cold-shock tested with liquid nitrogen, followed by proof-pressure testing to 2.5 MPa, and then helium-mass-spectrometer leak testing. The power lead is then subjected to a voltage potential of 5000 V between the conductor and ground. The high pot test is performed at room temperature in air at normal atmospheric pressure.

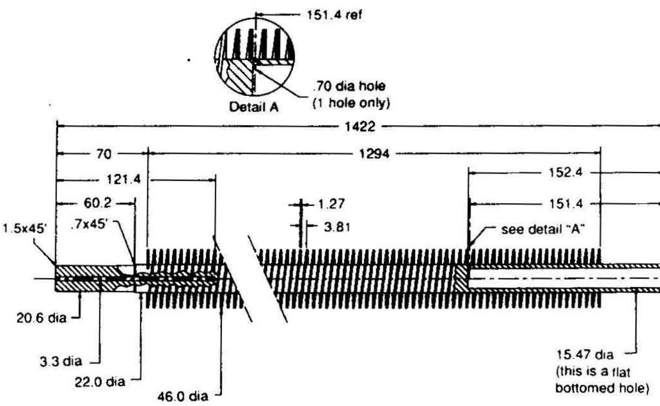

Fig. 6. Structure of the spiral-fin copper core.

The mechanical design of the vapor-cooled power lead was improved primarily by incorporating a stainless steel tube (pant leg) between the copper power head and the O-ring-sealed pressure boundary area (see Fig. 5) [9]. This design also incorporates a "folded" insulator tube assembly and vacuum insulation extending into the power lead assembly. These features provide good thermal performance and electrical isolation for the power lead assembly. A thorough investigation of the voltage breakdown characteristics of the power lead was conducted, and the design was modified accordingly to ensure adequate performance. The bolts of the insulator assembly extend into the insulator from the top and bottom into blind holes. This prevents a potential voltage leakage path (due to moisture) through a continuous single bolt hole that extends completely through the insulator assembly. The G-10 insulator flange will be sealed with varnish and epoxy to prevent moisture adsorption. Stainless-steel tubing sizes were selected to minimize thermal conduction while still meeting code

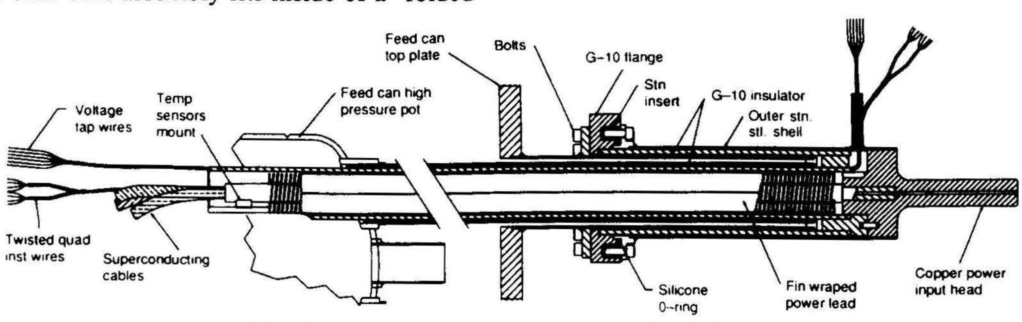

Fig. 5. Assembly structure of the 10-kA VCPL.

requirements for pressurized piping. A thin-walled stainless-steel tube is installed over the finned copper conductor in such a way as to prevent helium gas bypassing around the ends of the copper fins. The feed can mounting provision for the vapor-cooled power lead (shown in Fig. 7) was designed to accept multiple iterations of the power lead design.

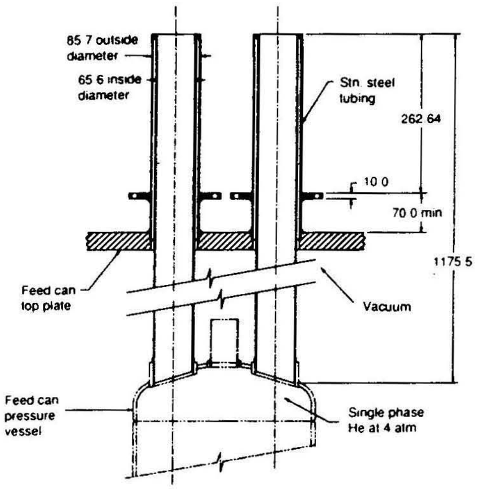

Fig. 7. Interconnect port of the MTL feed can pressure vessel to the power leads.

B. *Thermal Barrier Design*

During normal operations of a vapor-cooled power lead, transient conditions can occur that result in extremely cold temperatures at the electric power input connector. The gas seal area of current spiral-fin power lead designs is subject to temperature variations that result in seal leakage due to shrinkage or embrittlement, and electric leakage due to moisture condensation. In the design as shown in Fig. 8, a new device, known as a thermal barrier, is designed to reduce heat conduction from the vacuum and gas seal area of a power lead, thereby maintaining a warm temperature at the seal area during transient upsets. The electric insulation assembly, which isolates the ground-potential parts of the lead from the high-power parts, was moved into a warm region in order to prevent vacuum and helium leakage in the O-ring seals due to low temperature.

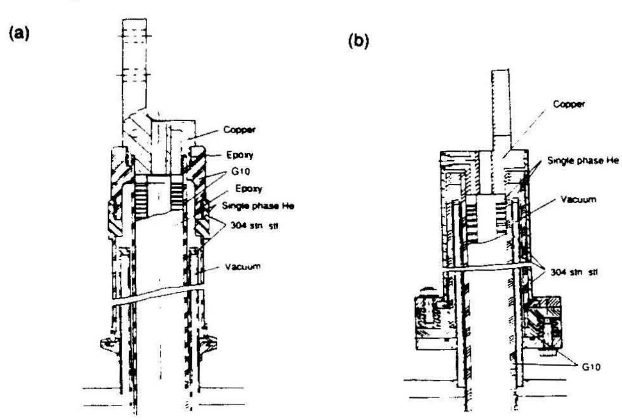

Fig. 8. (a) The previous Fermilab design. (b) The new SSC/Fermilab warm electric insulator design of 10,000 A-power lead assembly.

The replacement of the copper-to-stainless-steel bond thereby utilizes an approximately 50:1 reduction in the thermal conductivity of copper versus stainless steel.

IV. INSTRUMENTATION OF THE VCPL

In order to control and monitor the cryogenic operation, the VCPLs were equipped with temperature sensors, voltage taps and flow controllers [10]. Fig. 9 shows the schematic of the power-lead instruments. One PT-103 Lakeshore platinum thermometer is inserted at the top of each spiral-fin copper core with a special probe, and two CGR-1-1000 Lakeshore carbon glass resistor thermometers are mounted at the bottom of each lead. All thermometers have both good thermal contact with and proper electric insulation from the power lead. The five voltage taps for each power lead are used to monitor the resistance changes of the spiral-fin copper core and all the solder joints between superconducting cables. One MKS 1562A helium gas flow controller/meter (480 SLPM, ± 1% FS accuracy) is installed in each power lead return line at room temperature. The signal from the voltage taps is fed back to the magnet quench protection system. An over-voltage signal will cause the quench protection system to automatically shut off the power supply. Both the temperature signal and the resistance signal from the spiral-fin copper core will be fed back to a computer system to operate the MKS helium flow controller.

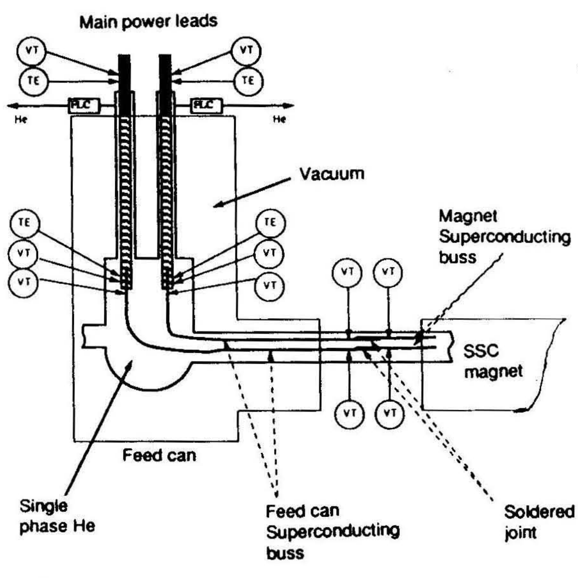

Fig. 9. Schematic of the VCPL instruments.

V. DISCUSSION AND PREDICTED OPERATIONAL CHARACTERISTICS

It is observed that both Fermilab and BNL designs of the VCPLs are in the recommended region based on our thermal analyses. The larger diameter of the VCPL corresponding to a larger thermal capacity is in favor of quench protection. Of course, a compromise must be made in determining VCPL parameters. The SSCL MTL 10-kA, vapor-cooled power leads have been manufactured at Fermilab and will be tested by the fourth quarter of 1992. The power leads will be installed into the feed cans in MTL for SSC magnet cryogenic test. The operational characteristics of the power leads were calculated.

In Fig. 10 the cryogenic system ideal Carnot work is shown as a function of lead flow. The figure indicates that there exists a lead flow that should be supplied to minimize the load on the cryogenic system for currents up to 5 kA. Above 5 kA the minimum lead flow required to maintain the lead-in stable operation will also provide the minimum cryogenic system work.

The reason for this can be explained by looking at Fig. 11, which shows the heat transfer to 4.2 K as a function of lead flow for the different operating currents. For low current operation, the lead flow reduces the 4-K heat leak by an order of magnitude. Thus there is a savings in refrigeration load that is offset by the increase in liquefaction load. At higher operating currents, the minimum lead flow required to maintain stable operation of the lead is sufficient to keep the cold end heat leak small.

The top end temperatures as a function of lead flow are shown in Fig. 12. The predicted temperatures are dependent on the heat exchange with the environment. Analysis indicates that it may be possible to control the lead flow and warm end heat transfer such that the top of the lead is above the freezing point of water.

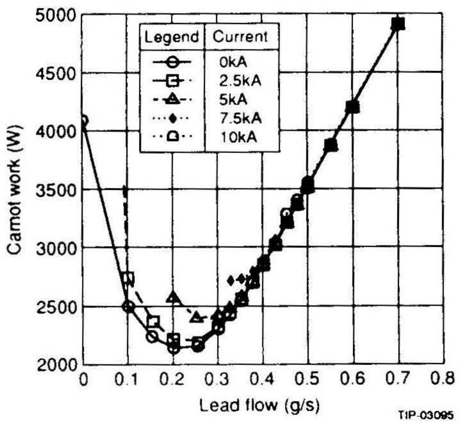

Fig. 10. The Carnot work of the MTL 10-kA VCPL as a function of the He flow rate in different operating currents.

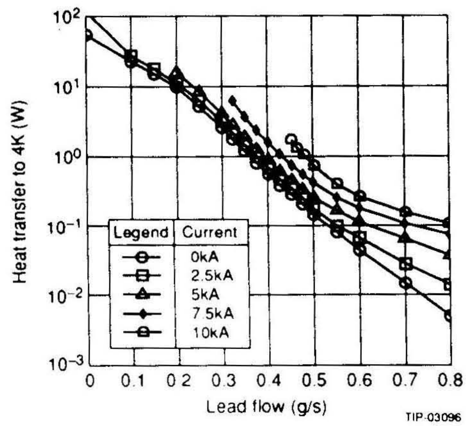

Fig. 11. Heat transfer to 4 K of the MTL 10-kA VCPL of RRR = 100 as a function of the He flow rate in different operating currents.

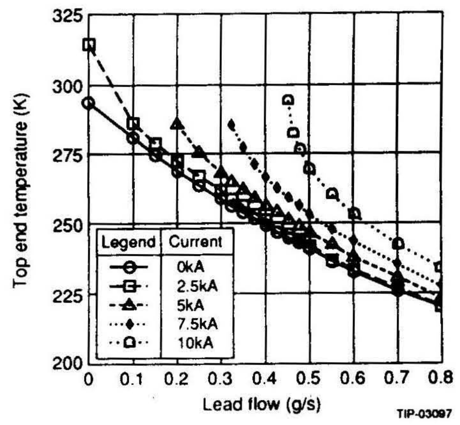

Fig. 12. Top end temperature of the MTL 10-kA VCPL of RRR = 100 as a function of the He flow rate in different operating currents.

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REFERENCES

[1] (a) Private communication with T. Peterson of Fermilab, July 1991.
(b) Fermilab 10-kA power lead assembly drawings, 1988.

[2] (a) Private communication with A. Prodell of BNL, August 1991.
(b) BNL 8.6-kA power lead assembly drawings, 1991.

[3] Private communication with M. Green of LBL, July 1991.

[4] Ben-Zvietc et al., "Current Leads for HERA," *Nuclear Instruments and Methods in Physics Research,* A276, 1989.

[5] Private communication with S. Schwenterly of Oak Ridge National Laboratory, July 1991.

[6] W. E. Schiesser, "A Dynamic Model of the SSC Power Leads," SSC Laboratory Informal Report, August 1990.

[7] J.A. Demko et al., "A Method of Lines Solution of the Transient Behavior of the Helium Cooled Power Leads for the SSC," *7th IMACS International Conference on Computer Methods for Partial Differential Equations*, Rutgers University, June 22–24, 1992.

[8] Q. S. Shu et al., "Optimum Thermal Design of the 10-kA Vapor Cooled Power Leads for the Magnet Cryogenic Test at MTL," MD-TA-213, MSD, SSCL, February 19, 1992.

[9] Q. S. Shu et al., "The Cryogenic System for the MTL Magnet Test Stands," *IISSC*, New Orleans, LA, March 4–6, 1992.

[10] Q. S. Shu et al., "MTL Cold Test Stand Instrumentation Design Specification," M62-000068, MSD, SSCL, 1992.