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A SUPERCONDUCTING (Nb-Ti) LIQUID HELIUM LEVEL DETECTOR

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A SUPERCONDUCTING (Nb-Ti) LIQUID HELIUM LEVEL DETECTOR*

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ABSTRACT

A superconducting liquid helium level indicator has been constructed and tested which utilizes a small Nb-Ti wire as the detector element. A heater creates and helps maintain a normal zone in that portion of the wire which is above the liquid helium level while that portion of the wire below the liquid level remains superconducting. Thus, the liquid helium level is determined by the position of the normal-superconducting boundary. The output voltage is very high (0.22 volts/cm at 50 mA) and varies linearly with a change in position of the liquid level. This device works in much the same way as previous detectors made with Ta or a Pb-Sn alloy, however, it has the added advantage that it can be used in high magnetic fields. Data and construction details are presented.

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INTRODUCTION

Superconducting coil systems are usually contained in metal dewars so that the liquid helium level cannot be viewed directly. The liquid level can be monitored at fixed points by means of various level detectors.[1-4] However, a simple detector which can give a continuous indication of liquid level is more desirable than fixed point detectors. A linear liquid helium level detector which uses a superconducting element of annealed Ta [5] and another using a Pb-Sn [6] alloy element fulfill the requirement of simplicity, however, neither of them can be expected to work except in very low magnetic fields. Another linear detector which relies on the measurement of the small capacitance difference between liquid helium and gaseous helium[7] should work in a magnetic field, however, the associated electronics is complicated and the system must be constructed with great care.

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[1] A. C. Rose-Innes, Low Temperature Techniques (D. Van Nostrand Co., Inc., Princeton, New Jersey, 1964) p. 9.

[2] R. V. Colvin, Sigurds Arajs, and D. S. Miller, Rev. Sci. Instr. **33**, 122 (1962).

[3] Aaron Wexler and W. S. Corak, Rev. Sci. Instr. **22**, 941 (1951).

[4] K. R. Canter and L. O. Roelleg, Rev. Sci. Instr. **37**, 1165 (1966).

[5] J. R. Feldmeier and B. Serin, Rev. Sci. Instr. **19**, 916 (1948).

[6] R. Ries and C. B. Satterhwaite, Rev. Sci. Instr. **35**, 762 (1964).

[7] W. E. Williams and E. Maxwell, Rev. Sci. Instr. **25**, 111 (1954).
S. Meiboom and J. P. O'Brien, Rev. Sci. Instr. **34**, 811 (1963).

A simple superconducting (Nb-Ti) liquid helium level detector has been designed and tested. The desirable characteristics of this detector are: 1) a continuous linear indication of liquid helium level, 2) a large signal output (0.22 volts/cm at 50 mA), 3) operation in a high magnetic field (75 kG), 4) relative ease of construction requiring no complicated electronics, and 5) reproducibility. The level detector utilizes the difference in heat transfer properties of liquid and gas phases of helium to produce and maintain a normal zone only in that portion of a high field superconducting wire (Nb-Ti) which is above the liquid level. Thus, the length of the detector which is above the liquid level is directly related to the normal state resistance of the Nb-Ti wire.

CONSTRUCTION DETAILS

Figure 1 shows a schematic diagram of two versions of the level detector. Figure 1a shows a high field superconducting wire (Supercon T48B, 0.004 cm O.D. with copper removed over active length) twisted together with a formvar insulated heater wire (#40 constantan). The combination is then coated with G.E. 7031 varnish to produce good thermal contact between the heater and superconductor. The heater and superconducting wires are soldered together at the lower end so that a series electrical current can be passed through the heater-superconductor combination by a constant current source. A voltage tap is connected to each end of the superconductor and the two taps are then connected to an external voltmeter. A light spring holds the heater-superconductor combination in tension to compensate for thermal expansion differences between the insulating tie points and the wires.

This type of detector has the advantage that it is bifilar and therefore not subject to any net forces due to magnetic fields. It has the disadvantage that part of the heater is below the liquid helium surface thus evaporating more liquid helium than might be desirable.

Figure 1b shows another version of the detector which utilizes only a small bifilar heater-superconductor combination at the top of the Nb-Ti wire to initiate a normal zone. For an appropriate operating current, the normal zone will propagate down the bare Nb-Ti wire to the liquid helium surface. This detector causes smaller liquid helium losses than the bifilar detector and should be used if magnetic forces are not important.

Figure 2 depicts a finished detector. The small wires are permanently mounted inside a hollow micarta cylinder (0.95 cm O.D., 0.159 cm walls) to protect them from accidental damage. The wires (including the lower potential tap) are stretched against a spring in the lower end and epoxied in place at the upper end. A slot in the side of the micarta tube insures that the liquid level inside the tube is the same as it is outside.

PRINCIPLE OF OPERATION AND EXPERIMENTAL RESULTS

When an appropriate constant current is passed through the bifilar sample, the heater generates enough heat to drive that portion of the superconductor above the liquid level (where the heat transfer is poor) into the normal state but not enough heat to affect the superconductor below the liquid level. Thus the total voltage drop across the Nb-Ti wire depends on the length of the normal section and, providing the superconducting wire is uniform and the temperature of the normal region is not so high as to change its resistivity, the voltage is directly proportional to the length of the normal section.

The operation of this device is best understood by observation of its voltage-current characteristic with a fixed fraction of the detector below the liquid helium level. Figure 3 shows results obtained for a bifilar detector. Note that with 10 cm of the detector in the gas a voltage appears almost immediately as the current is increased, indicating a normal zone at the top of the detector. As the current is increased, the voltage increases in a non-linear fashion as the normal zone grows toward the liquid helium surface. Finally when the current reaches about 40 mA, the V - I characteristic becomes almost linear as the current increases, indicating a constant resistance section above the liquid level. As the current is increased to about 105 mA, the normal zone begins to extend below the liquid level as the power dissipated becomes large enough to cause film boiling.[8] When the current is decreased to 100 mA, film boiling disappears and the normal zone below the liquid level disappears. A linear behavior results until the current is reduced below 35 mA at which time the power dissipated is insufficient to maintain a normal zone throughout the gas phase portion of the detector. Since the coldest portion of the detector is at the liquid helium surface, the superconducting zone grows from the surface toward the top of the detector as the current is decreased.

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[8] For example, see R. D. Cummings and J. L. Smith, Bull. Inst. Intern. Froid, Annex 5, 85 (1966).

The characteristic with only one cm of the detector above the liquid level differs slightly from that described above. The one cm section is in the coldest gas in the dewar, thus a normal zone does not immediately appear as the current is raised. Superconductivity persists until a current $I_o \approx 57$ mA is reached where the power generated by the heater is sufficient to cause a transition into the normal state. I_o has been found to vary unpredictably from one detector to another within the range 40 mA $< I_o <$ 70 mA. Variations in thickness and bonding of the varnish near the top of the detector could account for the differences in I_o. Operating at $I \geq I_o$ insures that the detector will function immediately when the current is turned on, regardless of the position of the liquid level. The operating current for the detector is limited to the linear region between the two hysteretic regions. Disregarding I_o, the minimum operating current is $I_{min} \simeq 40$ mA and taking into account the variable hysteresis loops at the high currents, the maximum current is $I_{max} \simeq 90$ mA.

The linearity of this device is most easily checked by using a sequence of V - I characteristics as shown in Fig. 3 to extract voltage vs depth curves for various constant currents. Figure 4 shows experimental values for the voltage across the length of the detector in gaseous helium with various constant currents. Straight lines are drawn through the experimental points to emphasize the degree of linearity (better than 1% for 30 cm detectors tested). Non-linearities can be caused by non-uniformities in the wire or by the higher temperature gas regions which occur near the room temperature portion of a dewar.[9] The

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[9] R. T. Swim, Advances in Cryogenic Engineering, Vol. 5, K. D. Timmerhaus, Ed. (Plenum Press, New York, 1960) p. 498.

latter case occurs because the normal state resistance of the Nb-Ti wire changes by about 4% from its transition temperature of $10.5^{\circ}K$ to liquid nitrogen temperature and about 20% from $10.5^{\circ}K$ to room temperature.

Tests were performed on a bifilar sample to determine the effects of magnetic field. The normal state Nb-Ti did not show any detectable magneto-resistance in longitudinal fields of 75 kG. Thus the calibration is not affected by magnetic fields. However, there are changes in the operating currents. Figure 5 shows that I_{min}, I_o, and I_{max} decrease with increasing magnetic field. This is undoubtedly due to the decrease in critical temperature of Nb-Ti as the magnetic field increases. Note that even at 75 kG there is still a large range of currents over which the detector will operate. The 75 kG longitudinal field was a large volume field and extended over the entire length of the level detector. No such transverse field was available, however a transverse field of 25 kG extending over 5 cm of the detector adjacent to the liquid helium surface was found to have no effect on its operation. Similar tests were not performed on the samples with the short heater, however, if the small magnetic forces inherent in this design are not important, this type of detector should also work in a magnetic field.

Although this detector works very well even in magnetic fields, the liquid helium losses must be shown to be reasonable to make it a practicle device. The maximum power dissipated in the detector occurs when the Nb-Ti is completely normal, i. e. when the entire detector is above the liquid level. The total power decreases as the level detector is submerged. All of the heat generated below the liquid helium surface will evaporate liquid while most of the heat generated above the liquid will be carried away by the helium gas. Helium losses were determined by measuring the rate of fall of the liquid helium level in a small dewar. Dewar losses were determined by operating the liquid level detector intermittently for very short periods to determine the liquid level as a function of time (negligible heat input by the detector). The sum of the dewar losses plus detector losses was determined by operating the level detector continuously and recording the level vs time. The detector losses were then determined by subtracting dewar losses. Figure 6 shows the results of liquid losses for both types of detectors for various depths of immersion when operated at a current of 70 mA and a bath temperature of 4.18 $^{\circ}$K. Note that the losses due to the bifilar sample are only slightly higher than would be expected for the submerged portion of the heater (straight, solid line). Also note that the losses due to the short heater detector are independent of depth and very small. Both of these results indicate that most of the heat generated above the liquid surface is carried away by the cold gas ($R = 0.97\ \Omega$/cm for #40 constantan and $R = 4.5\ \Omega$/cm for normal state T48B). Although the losses are quite small for both detectors, they can be reduced even further by operating the detectors intermittently rather than continuously.

It should be mentioned that these detectors have been used in helium baths with temperatures from 2.5 $^{\circ}$K to 4.2 $^{\circ}$K.

DISCUSSION

Detectors of this type have been used in various experimental systems in our laboratory for the past year. Three of the detectors have been installed in the relatively large superconducting coil system for which they were originally designed and are all working very well. The detector outputs are read on meters which are calibrated in inches of liquid helium and are also coupled to a time base recorder which is calibrated in liters of liquid, thus allowing determination of liquid loss rate. In other experimental arrangements, the detectors have been used to 1) determine helium losses, 2) to operate servo systems,[10] and 3) to determine positions of experimental equipment (to which detector was attached) relative to the liquid level. The detectors are usually used in conjunction with a small self-contained unit which consists of a constant current supply and a voltmeter which is calibrated directly in cm or inches of liquid helium.

Although this paper only describes detectors made of a particular heater-superconductor combination, other combinations can be used. For example, 0.0127 cm O.D. Nb-Ti (T48B by Supercon) and Nb-25% Zr (manufacturer unknown) superconductors have been used with #40 constantan heaters to form bifilar detectors. Short heater type detectors have also been constructed with the 0.0127 cm O.D. Nb-Ti wire. In general the larger superconducting wires tend to increase the operating current and helium losses. The minimum operating current for bifilar detectors is not easy to predict for various heater-superconductor combinations

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[10] K. R. Efferson, J. Appl. Phys. 40, 1995 (1969).

because of the uncertainty in heat transfer between heater and superconductor and the uncertainty of varnish thickness and thermal conductivity. However it seems obvious that increasing the ratio of heater resistance to normal state superconductor resistance will decrease the minimum operating current. The minimum operating current for the short heater type detector does seem to be predictable. If one assumes that the temperature of the normal state superconductor must be maintained at ΔT_c above the bath temperature and that the heat is transferred only to the gas, then one can write for a given superconducting material

$$\dot{q} = h\Delta T_c = \frac{4\rho}{\pi^2}\frac{I^2}{d^3} \qquad (1)$$

where $\dot{q}$ is the dissipated power per unit surface area, h is the gaseous heat transfer coefficient, ρ the normal state resistivity, and d the diameter of the wire. Then for two different sized wires

$$\frac{I_1}{I_2} = \left(\frac{d_1}{d_2}\right)^{3/2} . \qquad (2)$$

Using the experimental value of $I_2 = I_{min} = 40$ mA and $d_2 = 0.0043$ cm, we obtain for Nb-Ti (T48B)

$$I_1 = 1.42 \times 10^5 \, d_1^{1.5} \text{ mA}. \qquad (3)$$

Then for 0.0127 cm Nb-Ti one would expect $I_1 = 203$ mA which corresponds within exterimental error to the measured value.

Another point which should be mentioned is that both the bifilar and short heater detectors described in this paper have approximately the same range of operating currents, so that both the heater section and the monofilament section of the short heater type detector are active, i.e., the normal superconducting junction follows the liquid level faithfully as the liquid level crosses from heater section to bare superconductor section. When different ratios of heater resistance to normal state superconducting resistance are used, this is not necessarily true. For example, a bifilar type made of #40 constantan and 0.0127 cm O.D. Nb-Ti (T48B) has an operating range of 90 to 180 mA, whereas the single strand of Nb-Ti has an operating range of 200 to 300 mA. Thus, in a single strand detector using the #40 constantan and 0.0127 cm O.D. Nb-Ti, either the heater section would be active or the single strand section (depending on the current) but not both at once. Thus using a current of 200 mA to make the lower portion of the detector active will force the heater section to be normal at all times causing a zero shift in the voltage readout. These effects were mentioned primarily for the benefit of those who would like to vary the recipe from that given in this paper.

ACKNOWLEDGMENT

My thanks to W. H. Wagner and W. J. Schill for their assistance in construction and testing of the detectors and to J. L. Horton for designing the constant current supplies.

FIGURE CAPTIONS

Fig. 1a Bifilar detector consisting of heater (formvar insulated #40 constantan) in electrical series with 0.0043 cm O. D. Nb-48% Ti (Supercon T48B). Thermal contact between heater and superconductor is achieved by varnish.

Fig. 1b Superconducting wire as before but only a short electrical heater in series with the superconductor is used at top. Varnish is used on the heater section only.

Fig. 2 Detector element is usually mounted in phenolic cylinder to protect it from damage. Slot in side of cylinder is for liquid helium entrance.

Fig. 3 V - I characteristic for bifilar type detector (described in Fig. 1a) with length of detector above liquid used as parameter. Short heater type (Fig. 1b) has very similar characteristics.

Fig. 4 Voltage vs length of level detector above liquid helium surface as taken from data similar to that in Fig. 3. These results are applicable to bifilar or short heater detectors.

Fig. 5 Variation of I_{min}, I_o, and I_{max} as a function of longitudinal magnetic field for a bifilar type detector.

Fig. 6 Helium losses vs submerged length of level detector for bifilar detector (dots) and short heater detector (crosses). Solid line represents theoretical losses due to submerged portion of heater in bifilar detector. Dashed line is drawn in to emphasize independence of losses on position for short heater type detector.

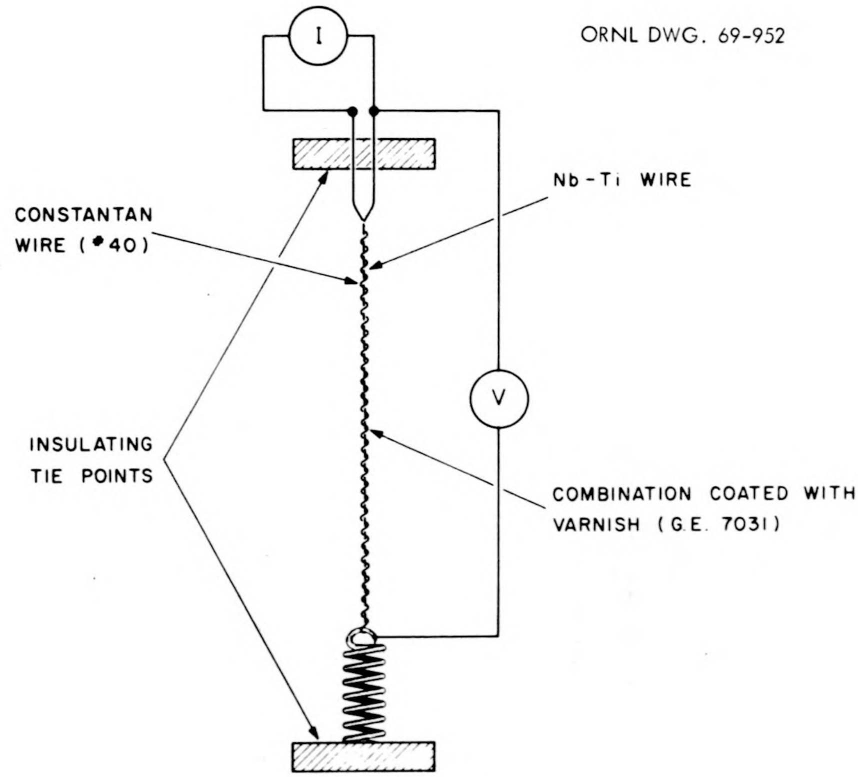

ORNL DWG. 69-952
I
Nb-Ti WIRE
CONSTANTAN WIRE (#40)
V
INSULATING TIE POINTS
COMBINATION COATED WITH VARNISH (G.E. 7031)

Fig. 1a

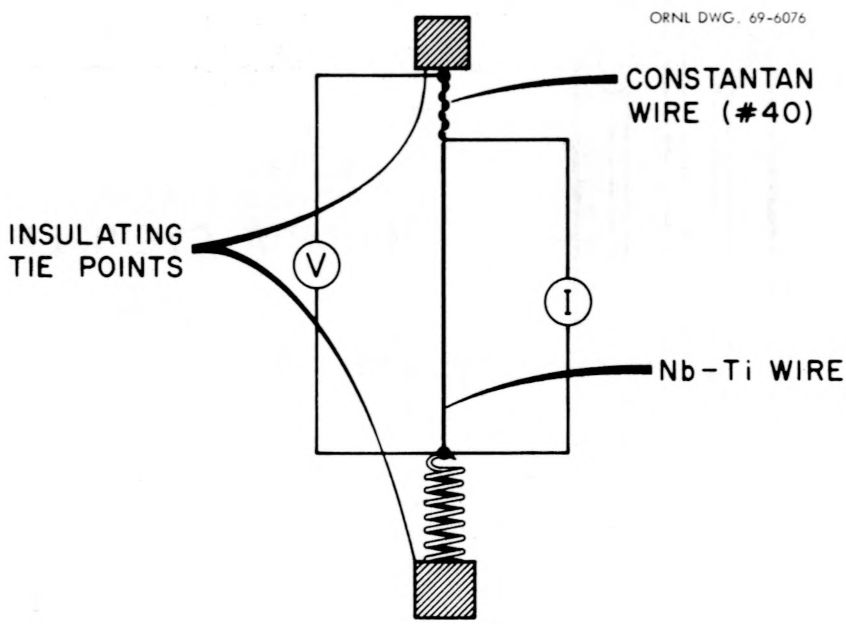

ORNL DWG. 69-6076
CONSTANTAN WIRE (#40)
INSULATING TIE POINTS
V
I
Nb-Ti WIRE

Fig. 1b

ORNL DWG. 69-951

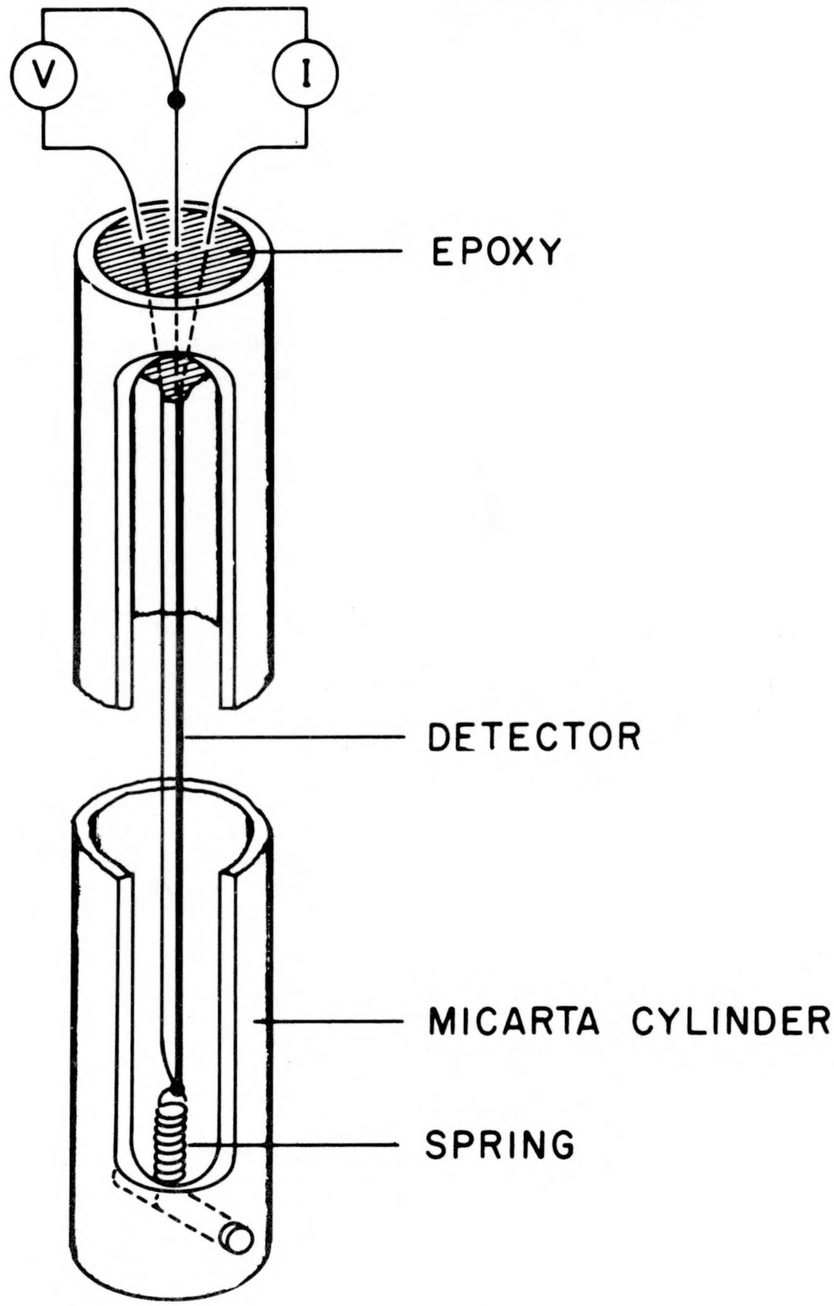
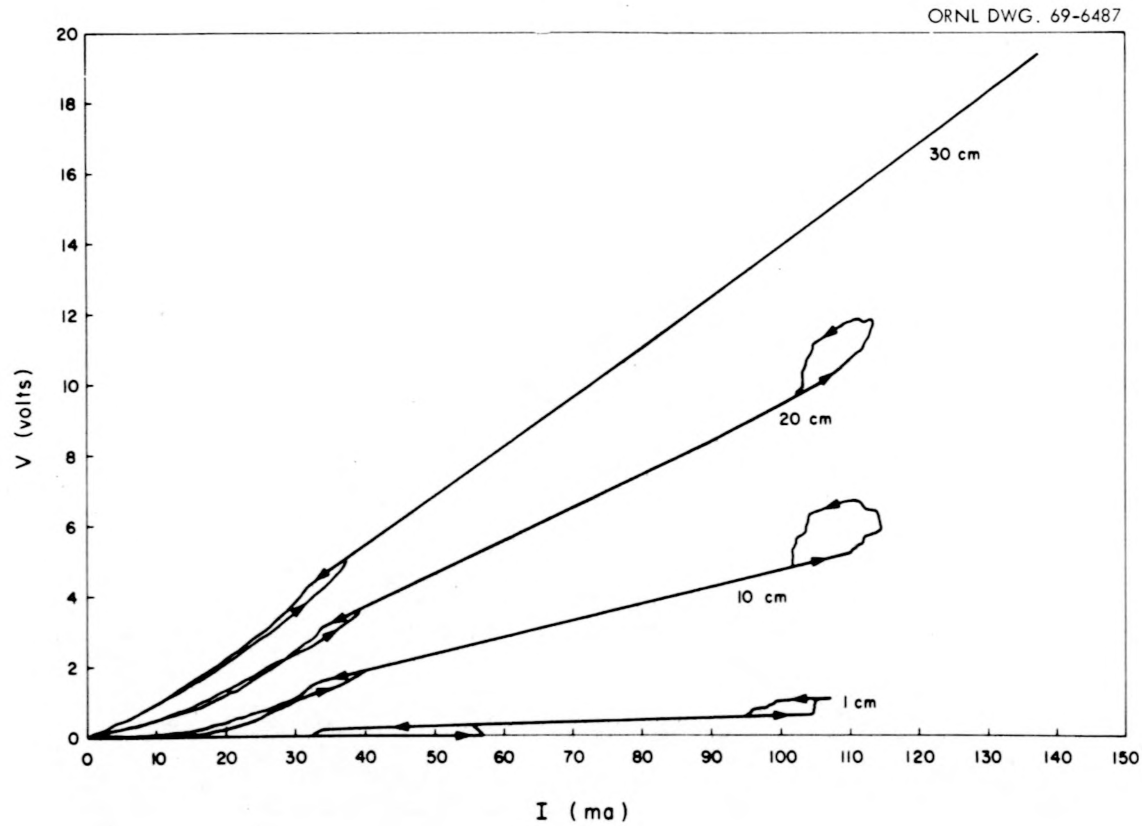


Fig. 2


ORNL DWG. 69-6487
V (volts)
I (ma)
30 cm
20 cm
10 cm
1 cm
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2
4
6
8
10
12
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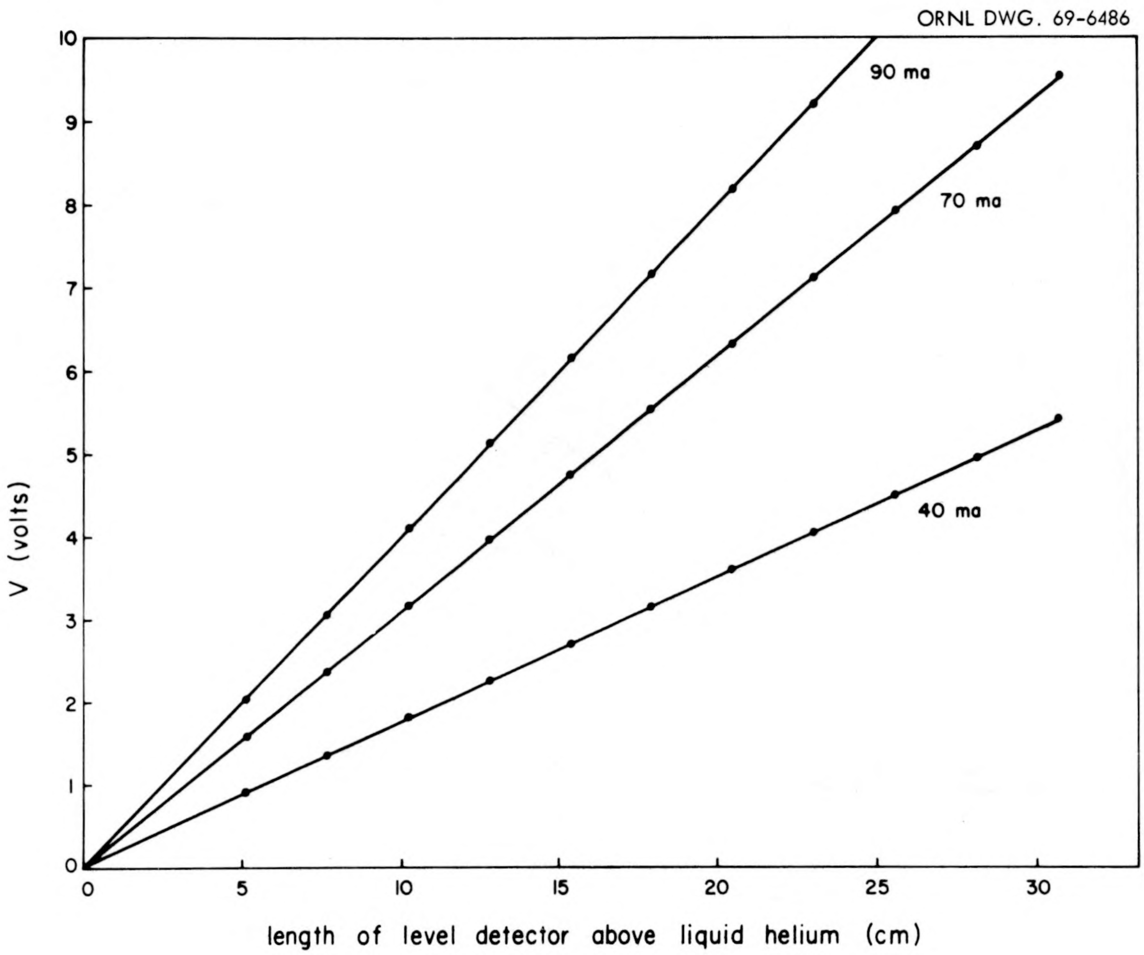
Fig. 3


ORNL DWG. 69-6486
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70 ma
40 ma
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1
2
3
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5
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7
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9
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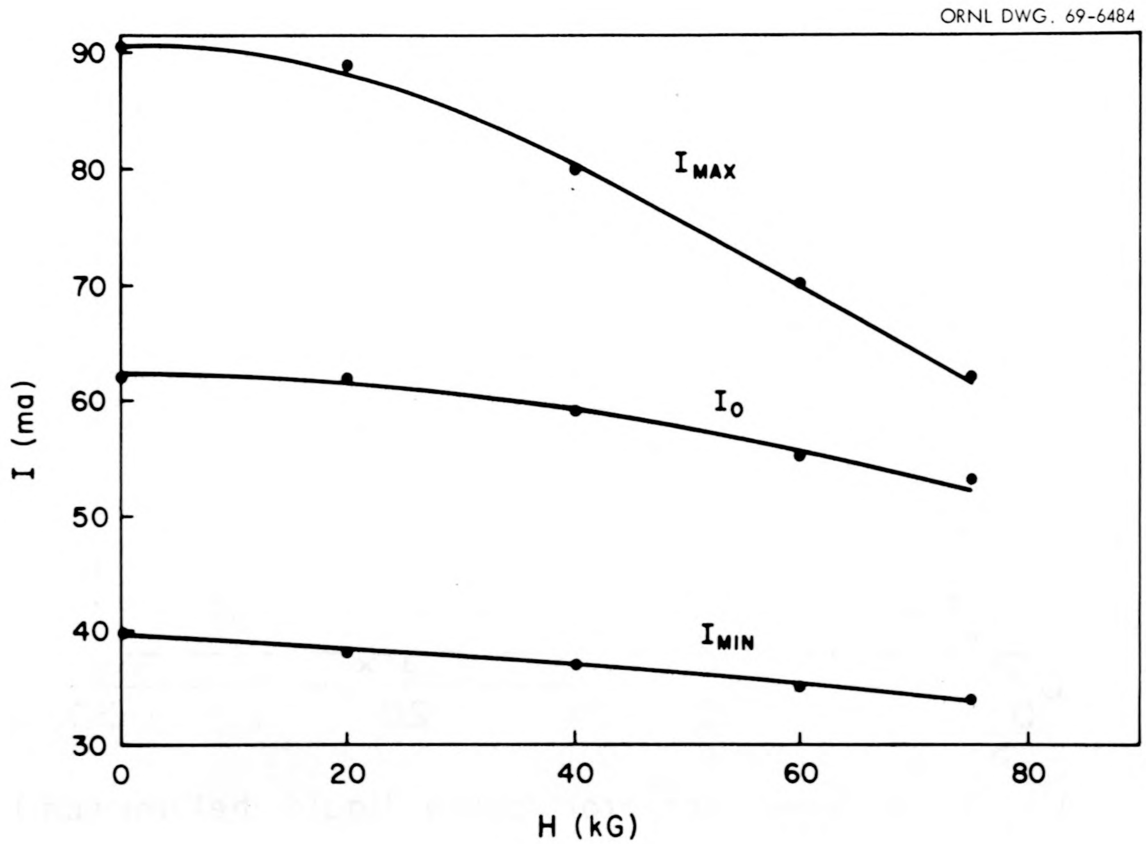
25
30
length of level detector above liquid helium (cm)

Fig. 4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80
H (kG)
I MAX
I 0
I MIN

Fig. 5

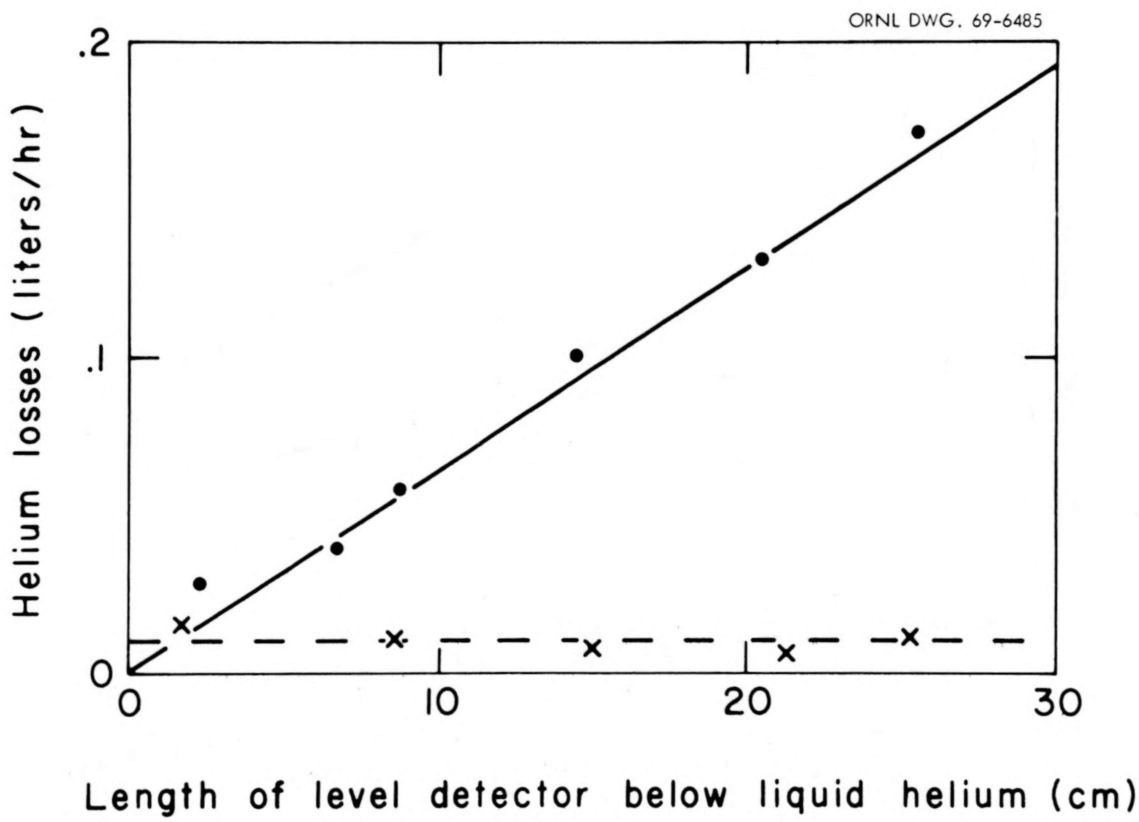
ORNL DWG. 69-6485
.2
.1
0
Helium losses (liters/hr)
0
10
20
30
Length of level detector below liquid helium (cm)

Fig. 6