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Precision Measurement of Magnetic Induction with Bismuth Wire

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ABSTRACT

The resistance of bismuth wire is a function of both temperature and magnetic induction. The change in resistance due to unit change in induction increases with decreasing temperature. Therefore, at low temperatures, the resistance of a bismuth wire probe may be taken as a measure of magnetic induction with high precision. It is thus possible with automatic recording equipment to plot directly magnetic induction versus any convenient co-ordinate.

PRECISION MEASUREMENT OF MAGNETIC INDUCTION WITH BISMUTH WIRE

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The needs of the laboratory have been such as to make the more or less classical methods of measuring magnetic induction no longer practical. In particular the familiar flip coil techniques are, (1) much too time consuming, (2) not reliable to accuracies of relative field measurement of 0.05 percent, (3) not suited to field measurements in high-gradient fields because of the difficulties in winding coils which sensibly measure the field at a point, and (4) strictly point-by-point rather than continuously measuring. As a consequence, the various methods of field measurement were re-examined.

Of all the methods of measurement of magnetic induction discussed in the literature, the one which appeals most from the standpoint of its neatness and adaptability to our requirements is the resistance-gauss effect exhibited by the element bismuth. The literature yields abundant information regarding attempts made to use this phenomenon.[1] Unfortunately as far as magnetic measurements are concerned, bismuth shows a large resistance-temperature effect in addition to the more desirable resistance-gauss effect, and, what is possibly more disheartening, crystalline bismuth is nonductile. Two problems had to be solved if we were to use bismuth for measuring magnetic induction. First, a satisfactory probe had to be constructed, and second, its temperature had to be carefully controlled. The first was largely solved for us by K. W. Fitzpatrick[2]. He has discovered a technique which allows him to extrude in diameters as small as 0.005 inch a ductile form of bismuth wire which is 99.999 percent chemically pure bismuth. Using this wire, which is supplied with analac insulation, we are able to wind, on teflon spools, non-inductive coils which have a room-temperature, zero-field resistance as large as 200 ohms, in a volume which does not exceed 0.003 in^3 (see Fig. 1). These coils are kept immersed in a constant-temperature bath (preferably a low temperature, because the lower the temperature the greater the change in resistance corresponding to unit change in magnetic field) during all measurements. To accomplish this, we have constructed a special dewar flask with a long side arm (see Fig. 2). The coil is located at the end of the side arm and the leads are brought out through the reservoir. The dewar is kept filled either with liquid Freon 12 or liquid nitrogen, the choice depending on the sensitivity required.

Reference to Table I shows the obvious advantages of choosing liquid nitrogen as far as sensitivity is concerned. This is particularly true when it is necessary to measure fields which do not exceed 2000 gauss. In general, however, it is more convenient to operate at the higher temperature of Freon 12, at which less difficulty is experienced in keeping the system free of water ice. It is also noted that, for those applications which require only occasional use of such equipment, the refrigerant storage problem is much less severe for Freon 12 than for liquid nitrogen, since Freon 12 is supplied as a liquid under pressure in steel cylinders which can be stored indefinitely.

The resistance of bismuth is, at any temperature a nonlinear function of magnetic induction. However, at the boiling point of Freon 12 (about -28° C) and for field values greater than 5000 gauss, the function can be approximated to an absolute accuracy of 0.1 percent by a straight line equation of the form $B = a(IR) + b$, where B is in gauss, R is in ohms, and I is in amperes. A standard recording potentiometer may be used to record the resistance of a bismuth wire probe, and hence magnetic induction, if a constant current is passed through it, for then the IR drop across the probe is directly proportional to its resistance. This is conveniently accomplished to an accuracy of 1 part in 1000 by using a regulated 325 volt direct current supply, in conjunction with suitable precision current-limiting resistors, to obtain current values not to exceed 0.004 ampere for wire 0.005 inch in diameter. Heating effects impose the limit of 0.004 ampere on the probe current for 5 mil wire. More elaborate systems can be devised which maintain the current constant to a greater accuracy, but most applications do not require this since any change in the current due to an increase in the resistance of the bismuth wire is simply absorbed in the calibration of the probe.

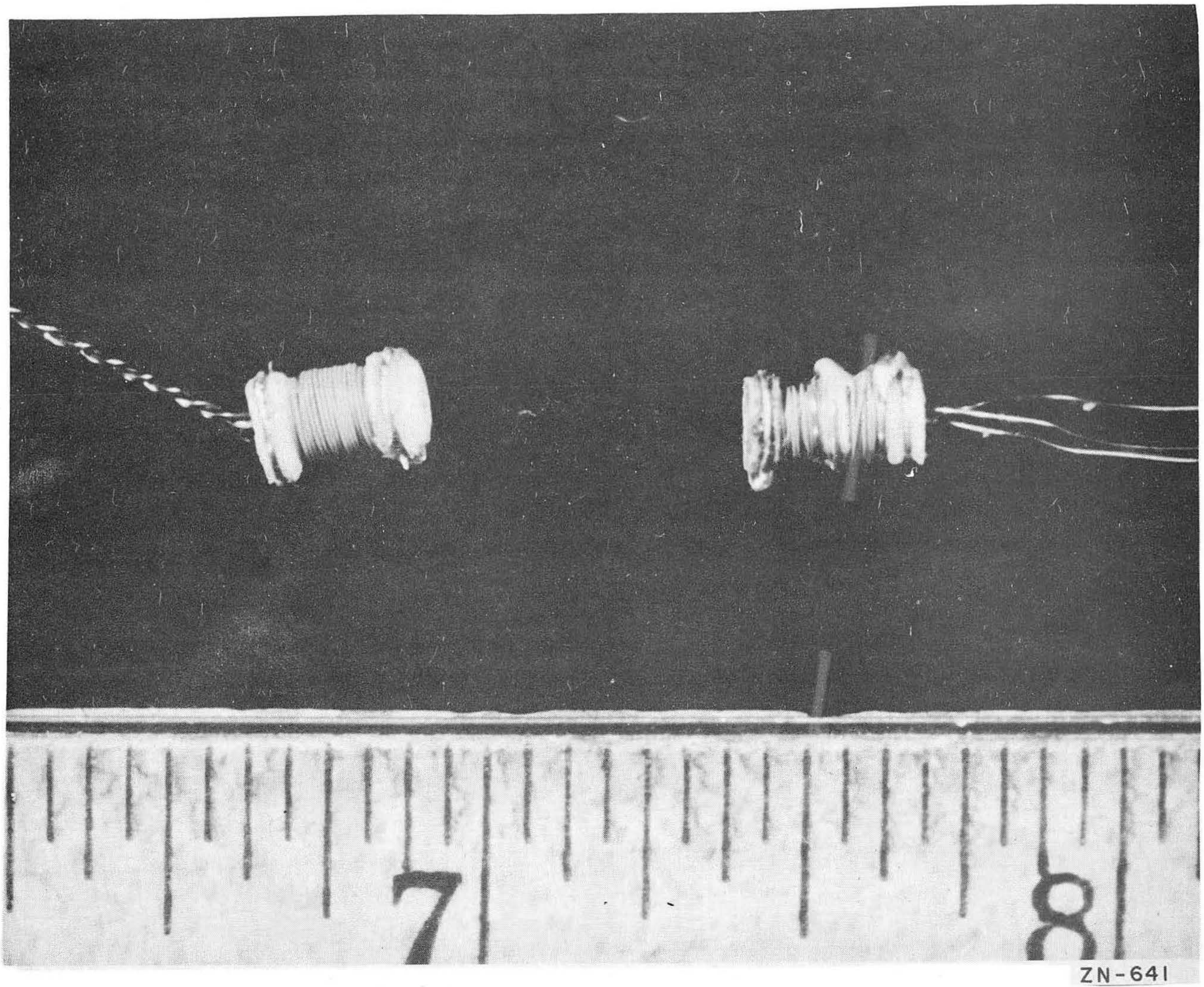

Fig. 1

Bismuth probes used to measure, respectively, magnetic induction and the directional derivative of magnetic induction.

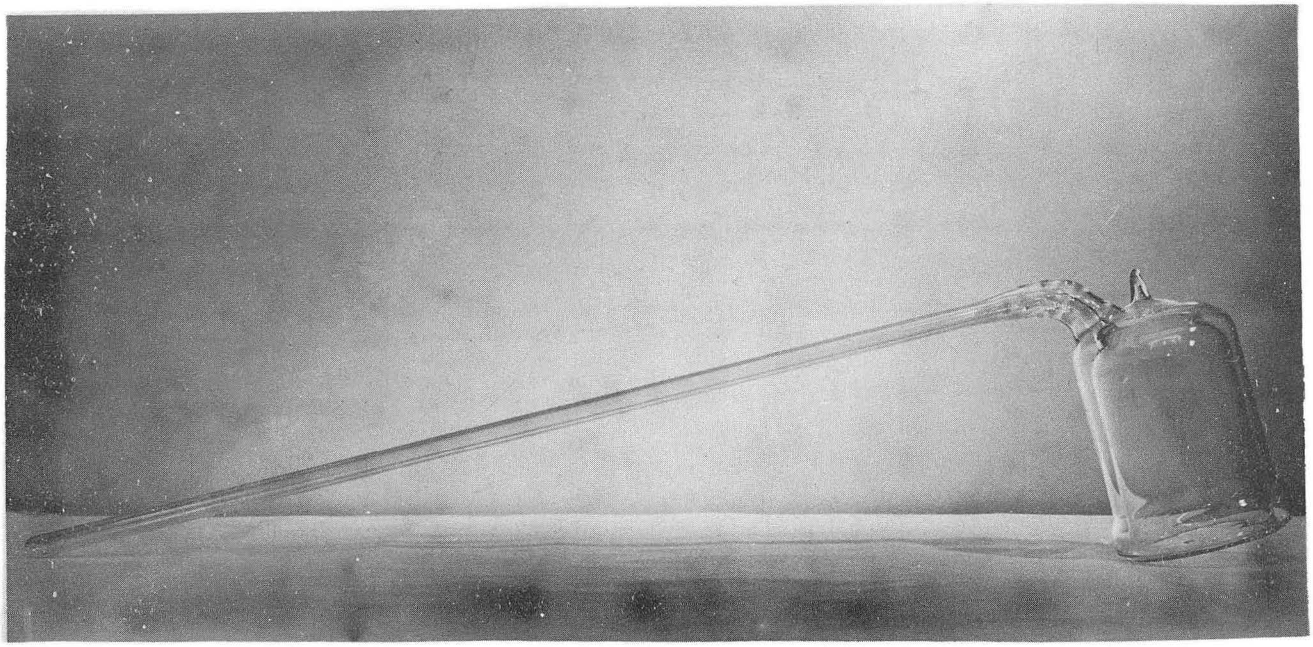

Fig. 2

Unsilvered side-arm probe dewar.

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The probe current is determined by the accuracy with which the field must be known. For most applications a sensitivity which corresponds to 0.1 millivolt deflection, as measured by a 0-10 millivolt potentiometer, for a change in the reference field strength of 0.1 percent, is quite adequate. Stated another way, it is desirable that 100 percent magnetic induction correspond to an incremental output from the bismuth probe of 150 millivolts. These sensitivities can always be achieved without the use of d. c. amplifiers of any description. The long time stability that one is therefore able to achieve is exceptional; the instrument is essentially drift free. In cases where the current regulation on a magnet exceeds 1 part in 5000, we have been able to repeat to better than 1 part in 1000 absolute measurements over an 8-hour period.

The following are the methods used to calibrate bismuth probes at the temperature of boiling Freon 12:

(1) For fields greater that 5000 gauss it is only necessary to determine the relationship between gauss and bismuth IR drop at two points using (a) a regulated electromagnet and a nuclear fluxmeter, (b) a Helmholtz coil, or (c) two permanent magnets whose field strengths are known exactly. These data are then used to determine the equation of a straight line; field strength (> 5000 gauss) is then given as a linear function of measured bismuth -probe millivolts. The limitation on the precision of this calibration is the accuracy with which the slope of the straight line portion of the calibration curve can be determined. The probable error should not exceed 0.1 percent.

(2) For fields less than 5000 gauss it is necessary to determine experimentally the exact shape of the gauss-bismuth millivolts function using methods as mentioned in (a) or (b) above. Once these data are accurately known the calibration of all bismuth probes can be deduced as follows: Suppose for one bismuth probe that field as a function of resistance is known for all values of magnetic induction that are of interest. Then $B = f(IR)$ is known in tabulated form and, further, it is known that the function has an asymptote $B = a(IR) + b$. Suppose further that for a second probe the asymptote only is known and has the equation $B = a'(IR') + b'$. Then for identical materials both a and a' and b and b'

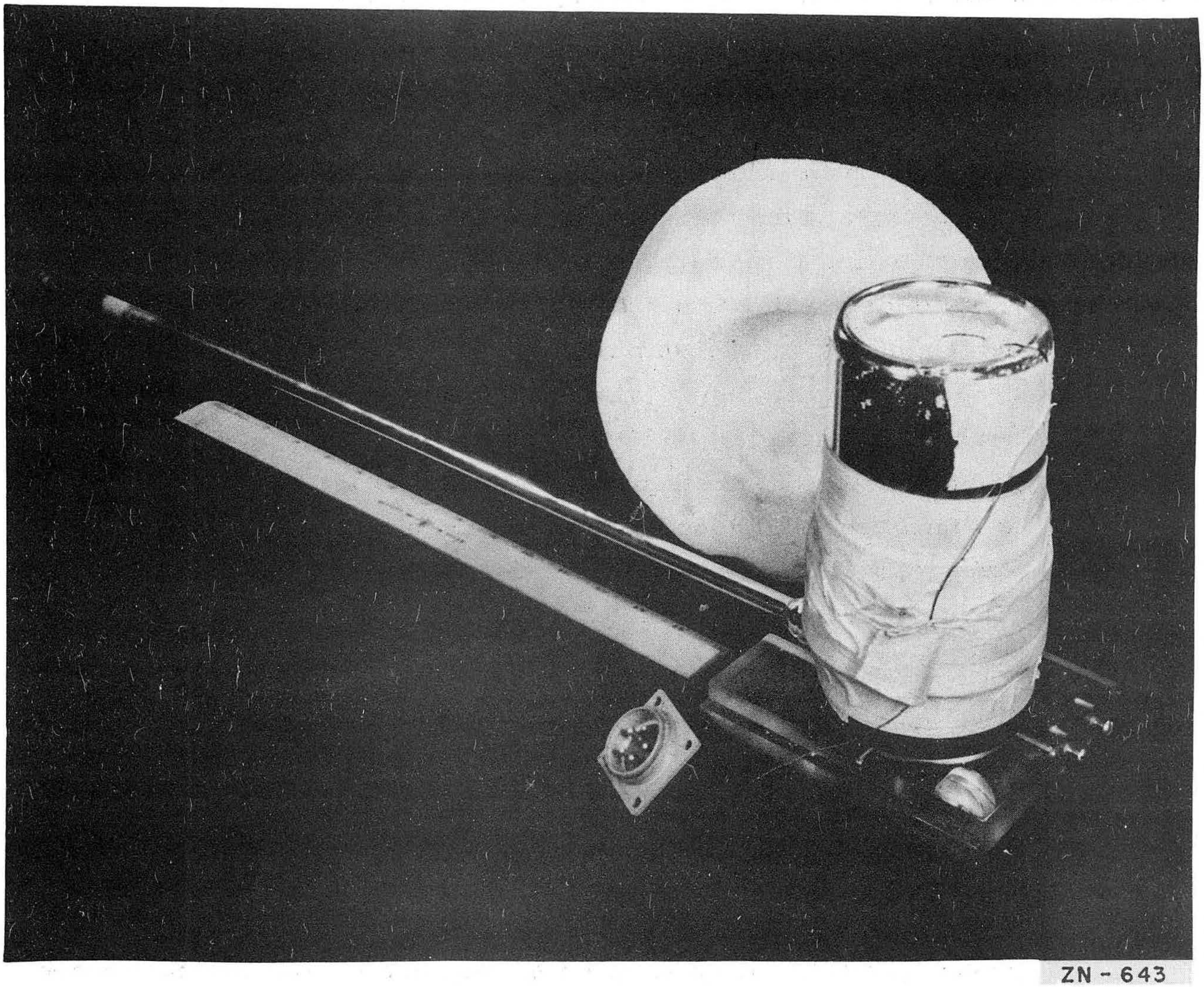

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Fig. 3

Bismuth-probe boat.

would be related by the same constant. Therefore, using the transformation equation $R' = KR$, we get $B = f(IR) = f(\frac{IR'}{K})$. This means that one probe can be calibrated in terms of another simply by an accurate determination of the constant K.

At liquid nitrogen temperatures, the general shape of the function relating magnetic induction and bismuth millivolts is the same as at Freon 12 temperatures with one important exception. The function cannot be approximated by a straight line except at field values which exceed some 20,000 gauss. The discussion of (2) above therefore applies for all values of magnetic induction.

The physical size of the bismuth probe and its zero-field resistance is determined in part by the size of the magnet with which they are to be used. Much of our work has been with model magnets, and as a result the emphasis has been on keeping the probe volume as small as is compatible with adequate sensitivity. For most of our applications, the largest linear dimension of the probe has been kept to less than one-tenth the minimum magnet gap distance. Under these circumstances any variations in the magnetic induction across the probe introduce a negligible error.

The 5-mil bismuth wire is wound noninductively on small teflon spools; twisted leads of No. 30 formvar-covered copper wire are connected to the bismuth wire and the spool in such a way that the bismuth wire is not under stress. The electrical connection between the copper wire and the bismuth is made using either Wood's metal or printed-circuit silver paint.

The latter seems to show aging effects at liquid-nitrogen temperatures; the former must be applied skillfully to avoid any growth in the grain structure of the bismuth wire due to overheating, since small grain size is directly related to ductility. A probe that has been carefully constructed gives months of dependable service. Opening up of the probe can in most cases be traced to improper or careless handling.

The dewar in which the probe is mounted is incorporated in some suitably designed holder, hereafter referred to as the "probe boat" (see Fig. 3) which is made to move in a system of co-ordinates that is convenient for the particular survey in question. Figure 4 shows the way we have solved the mechanical problems associated with an azimuthal-type survey. The granite surface plate is mounted perpendicular to the axis of the magnet. The probe boat then describes a circular motion on the plate; the alignment of the system

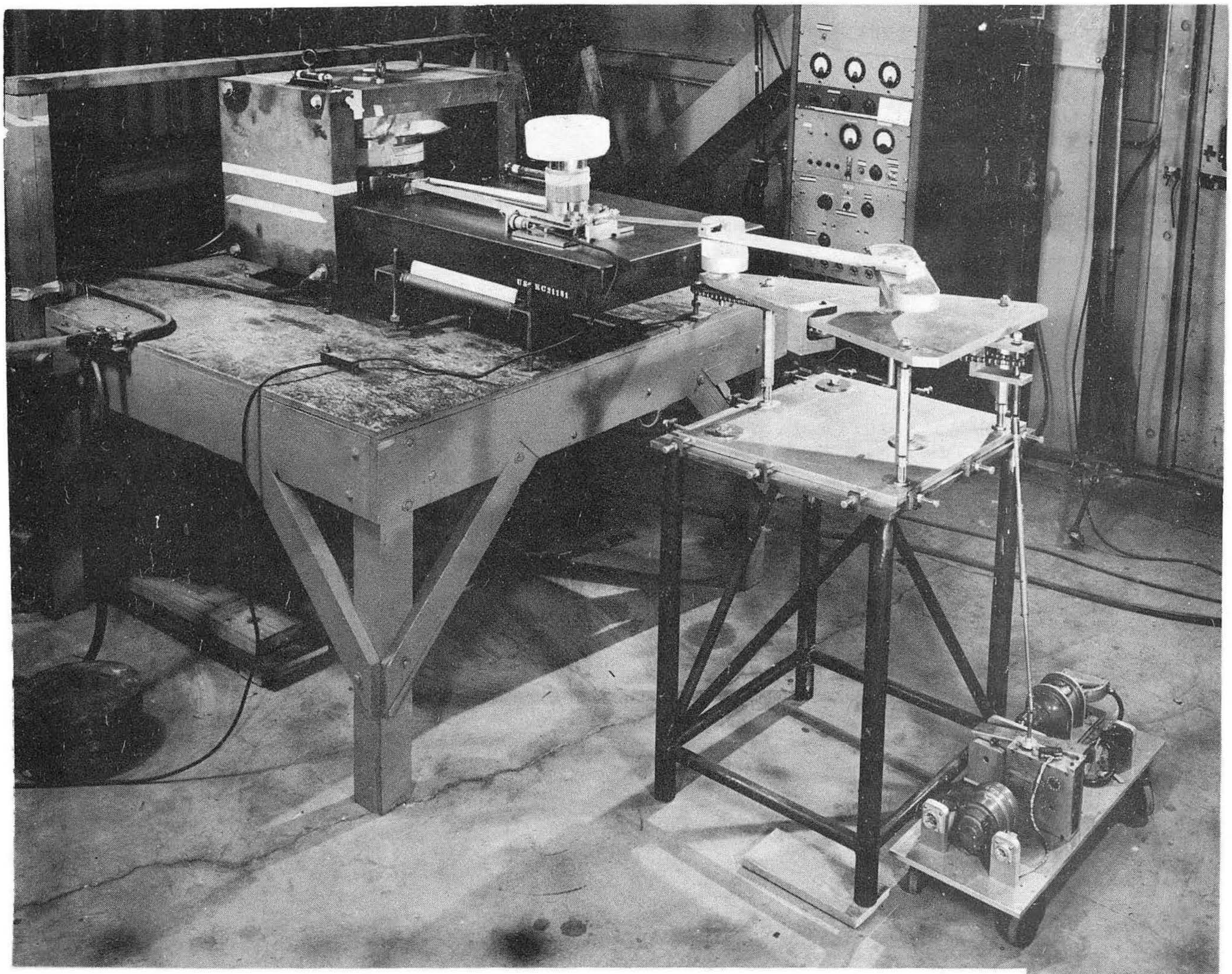

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Fig. 4

Drive mechanism associated with an azimuthal-type survey of a model magnet.

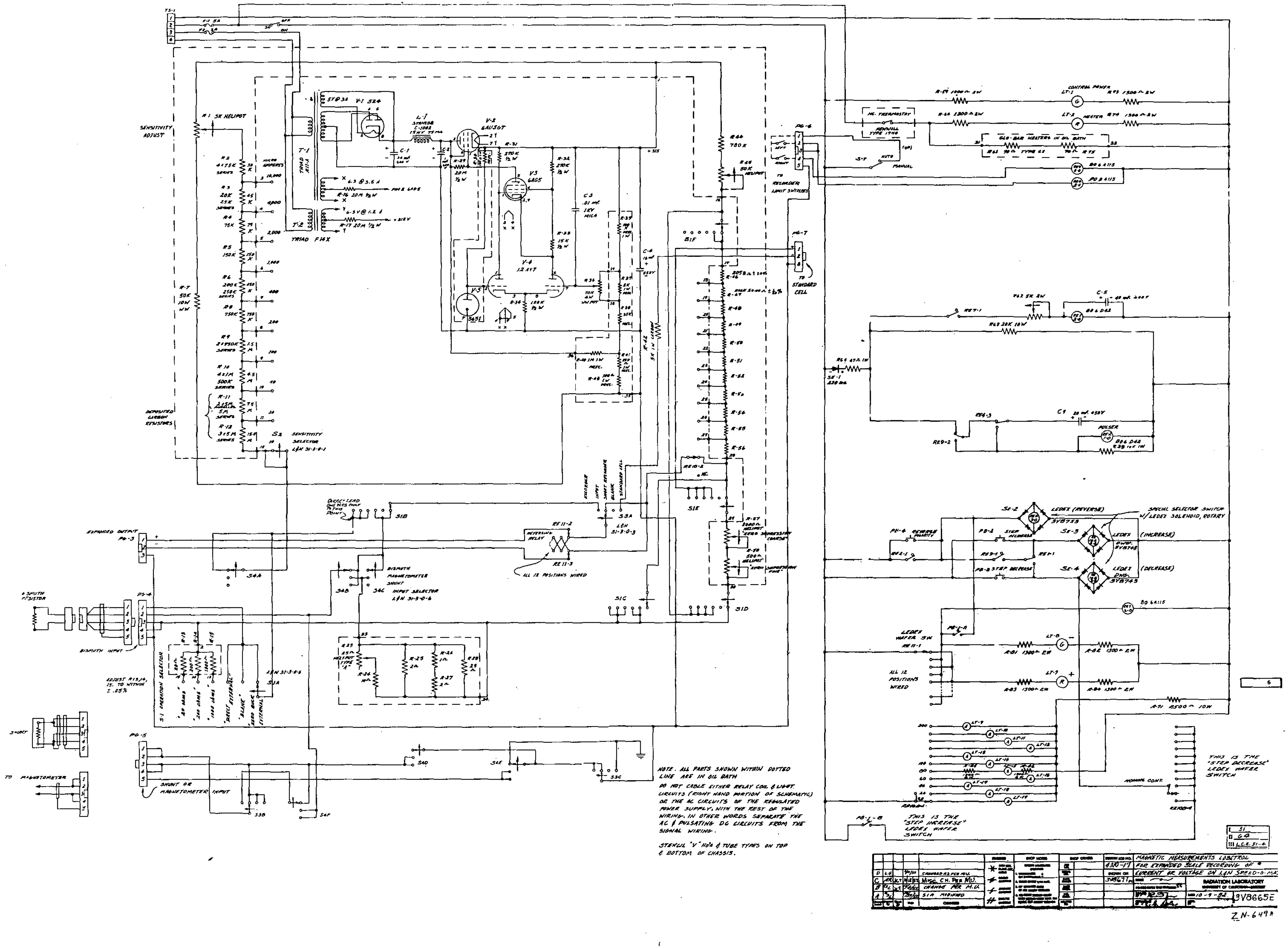

Fig. 5 Schematic diagram of a lobetrol.

is such that the probe moves azimuthally with respect to some preselected reference point. For most applications polar co-ordinates are preferred; the azimuthal survey runs are made sufficiently close together in radius to guarantee that the field will be known everywhere to within some predetermined relative accuracy. These runs are then tied together by a diametrical run as a further check on the stability of the entire system.

Recording Techniques

1. Co-ordinate

a. In this setup both the recorder chart paper and the probe boat are driven independently by synchronous type a.c. motors. When the operator is sure that both motors are operating synchronously, and when the relative speeds of the chart paper and boat are known, then there exists a factor which relates inches of boat travel to inches of chart paper. Pip markers are used to indicate on the chart paper the position of the bismuth probe in the magnet.

b. Chart paper and probe boat are driven by the same d.c. motor. In this case, the synchronous chart-drive motor is replaced by a selsyn receiver. A selsyn transmitter is driven by the d.c. motor. The gearing of the system is adjusted so that one inch of boat travel in the magnet corresponds to some whole number of inches of chart paper. The chief advantage of this system is that the boat speed may be adjusted so that the recorder pen can keep up with the probe boat in fields that vary rapidly with co-ordinate.

The co-ordinate in either of the above cases could be degrees quite as well as inches.

2. Recorder

A standard Leeds and Northrup Speedomax, type G, -1 to + 11 mv, is the basic unit with which we began. It is obvious that one could not record, say, 15,000 gauss to a relative accuracy of better than 0.1 percent on a 10 millivolt scale. Mr. C. G. Dols and the author have devised an automatic range extension device, hereafter called "lobetrol", which may be used with any standard recorder equipped with limit switches, to extend its range without sacrifice of resolution. A standard lobetrol unit (see Fig. 5) permits voltages as large as 210 mv to be read on a 10 mv recording instrument. The chief virtue of the lobetrol lies in its ability (1) to sense whether the input voltage signal is increasing, decreasing, or reversing, and (2) to follow these changes automatically and continuously. The generalized operation of the lobetrol is taken up in Appendix A.

Some of the more elaborate recording techniques that have been used are as follows:

a. The standard recorder is replaced by a dual-pen speedomax and used with two lobetrols. One lobetrol and pen combination records magnetic field. The second records magnet current or the field at some reference point. Any variations in the current or the field at the reference point thus form a part of the permanent record (see Fig. 6).

b. The standard recorder is replaced by a single pen, X-Y recording speedomax and used with two lobetrols to plot magnetic induction directly as a function of magnet current. If magnet current is increased slowly as a function of time, then a complete magnetization curve is plotted with 0.1 percent resolution on a piece of paper 10 inches square (see Fig. 7).

c. Some applications require greater relative accuracy (say 0.01 percent); it is then advisable to use a Leeds and Northrup automatic recording resistance bridge modified to read any 100 ohms in the range from zero to 2000 ohms (see Appendix B). To give some idea of the resolution possible, consider a probe that is 115 ohms at zero field and room temperature. At liquid nitrogen temperatures it has a resistance of about 45 ohms at zero field; this increases to about 2000 ohms at 18,000 gauss, or stated in terms of instrument deflection, 10 inches is roughly equivalent to a field change of 10 gauss.

The extreme resolution of this instrument makes it feasible not only to record the magnetic induction but also to record simultaneously, and with good accuracy, the directional derivative of the magnetic induction. To do this a special probe is constructed consisting of two bismuth coils mounted in tandem (Fig. 1). If the axis of this probe moves tangent to its direction of motion in the field, then the difference in resistance of the two coils due to the fact that they are located in fields of different strengths is proportional to the directional derivative in the direction of the motion. How they are connected to the bridge and a lobetrol is detailed in Appendix C. The output from one probe is recorded as magnetic induction while the resistance difference between the probes is recorded on the bridge as the directional derivative. So that both pieces of data may be presented simultaneously on the same piece of chart paper, one pen of a dual-pen recorder is used to record the magnetic induction, while the second pen is connected as a slave unit to the self-balancing bridge; that is, the second pen of the dual-pen recorder and the bridge pen are made to indicate together (see

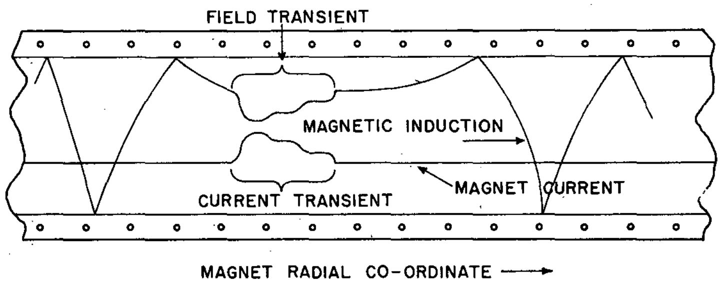

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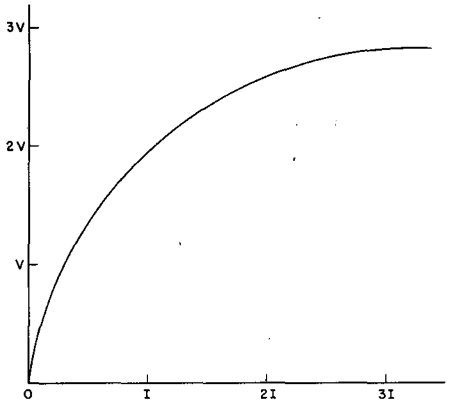
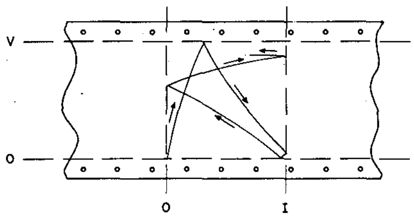
Fig. 6

Transient phenomena are readily recognized when current and magnetic induction are plotted simultaneously on the same piece of chart paper.



(a) DATA TO BE RECORDED



(b) SAME DATA, BUT FOLDED IN TWO DIRECTIONS FOR RECORDING PURPOSES

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Fig. 7

Illustrates X-Y folded scale recording.

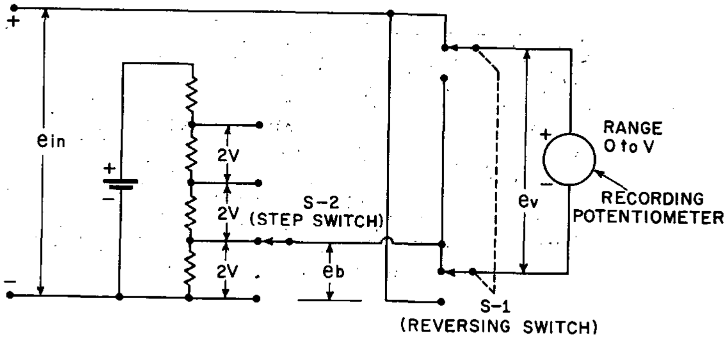

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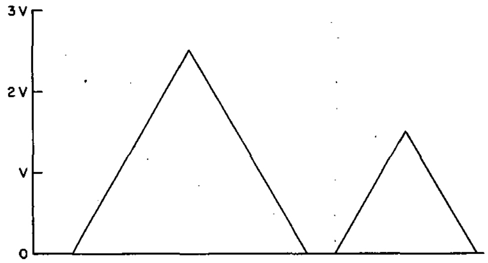
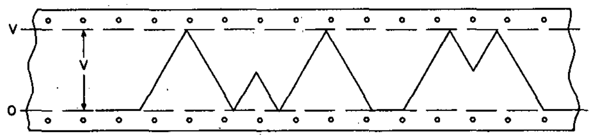
Fig. 8

Basic range-extension circuit of a lobetrol.



(a) DATA TO BE RECORDED



(b) SAME DATA AS ABOVE BUT FOLDED ON A NARROW CHART

MU 5653

Fig. 9

How narrow charts display high-resolution data.

Appendix D). Thus, for constant magnet current, the co-ordinate, magnetic induction, and the directional derivative of the field may be simultaneously recorded.

Appendix A

Extended-range recording with a lobetrol:

The circuit used is shown schematically in Fig. 8. The voltage to be measured $e_{in} = e_b \pm e_v$. When $e_b = 2nV$ (where n is any integer from zero to n inclusive), and the self-balancing recording potentiometer covers the range from zero to V, then any e_{in} between -V and $(2n + 1)V$ can be measured. The important features of this system are (1) for a given number of voltage steps V, twice the range is covered, and (2) with a relatively slow recording instrument the trace of e_{in} is interrupted only while the switches are moving from one position to another.

The generalized operations which must be initiated automatically in using the above scheme are:

a. When the voltmeter reaches its lower limit, reverse its polarity with S-1.

b. If e_{in} is increasing and the voltmeter reaches its upper limit, reverse its polarity with S-1 and increase e_b one step with S-2.

c. If e_{in} is decreasing and the voltmeter reaches its upper limit, reverse its polarity with S-1 and decrease e_b one step with S-2.

d. If e_{in} is either increasing or decreasing and then reverses, the decision must be made whether condition (b) or condition (c) applies, and action carried out accordingly.

The lobetrol is designed to sense and respond to these conditions automatically. A detailed discussion of its sequential operation is found in UCRL-2049. The result of following this procedure is that data from the curve shown in Fig. 9(a) would be folded and plotted as in Fig. 9(b).

Appendix B

Modification of a Leeds and Northrup automatic recording resistance bridge to measure resistances greater than 100 ohms:

As shown in the much simplified diagram of Fig. 10, the basic bridge is designed to be connected to an unknown resistor X as in (a). When this is done the instrument has a range R from zero to 100 ohms. If, however, a

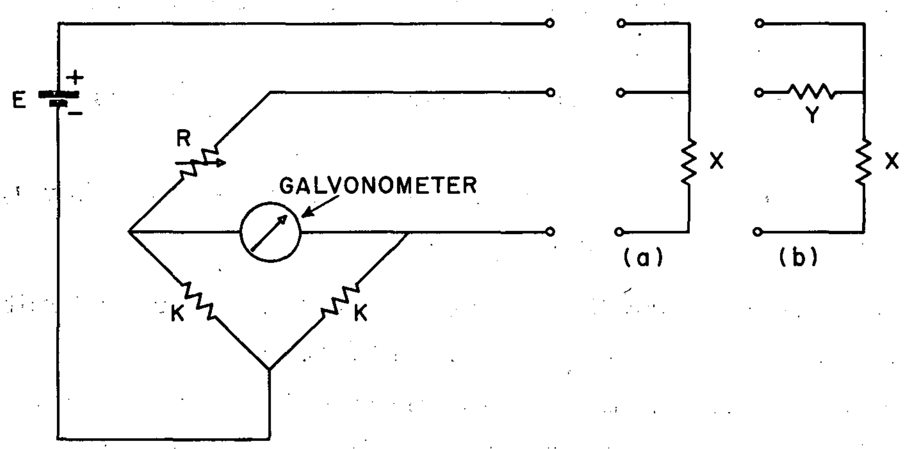


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Fig. 10

External circuit change which allows the range of a Leeds and Northrup automatic recording resistance bridge to be extended.

resistor box Y is connected in as in (b), then the range is extended to Y + R ohms. In this way the range may be extended to 2000 ohms. The upper limit on further range extension is imposed by the inability of the battery E to provide a sufficiently large and noise-free incremental voltage across the galvonometer to correspond to unit change in X.

Appendix C

Simultaneous measurement of magnetic induction and its directional derivative: Another way of looking at the connections of Fig. 10(b) is that the automatic recording resistance bridge measures the difference between Y and X, provided Y + R $\gg$X. If Y and X are two similar bismuth probes, mounted in tandem, and in line with the direction of motion, then the difference in their resistances is directly proportional to the directional derivative of the field in the direction of motion of the probe. The two probes need not be identical since the constant of proportionality may be determined experimentally.

A standard lobetrol may now be connected across either of the probes and the magnetic induction measured simultaneously.

Appendix D

Slave-unit recording:

Schematically, the circuitry necessary to make the X_1 pen of the dual-pen recorder function as a slave unit for the automatic recording resistance bridge is given in Fig. 11. This represents only a small change from the existing circuitry. The 1000 ohm potentiometer is a GR-314 modified for 320 degree rotation of the slider. This potentiometer is mounted in tandem with the slider-driving mechanism of the automatic recording bridge. How nearly the two recorders read the same is dependent on the linearity of the GR-314 potentiometer.

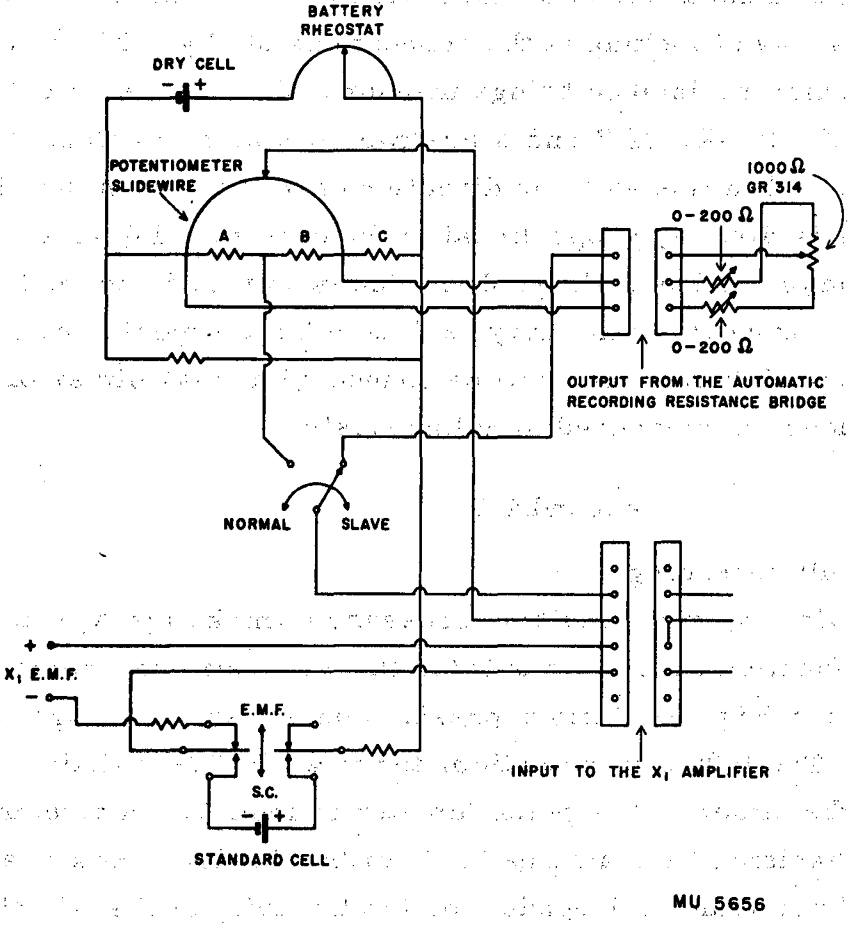

Fig. 11

The modified circuit of the X_1 section of a dual-pen Speedomax which functions as a slave unit for an automatic recording resistance bridge.

Table I

The following table gives the proportional values of resistance of bismuth at four temperatures and at various magnetic fields. The data is taken from the tables of the Smithsonian Institute.

B Kilo-gauss	-192°C	-37°C	0°C	+18°C
0	0.40	0.88	1.00	1.08
2	1.16	0.96	1.08	1.11
4	2.32	1.10	1.18	1.21
6	4.00	1.29	1.30	1.32
8	5.90	1.50	1.43	1.42
10	8.60	1.72	1.57	1.54
12	10.8	1.94	1.71	1.67
14	12.9	2.16	1.87	1.80
16	15.2	2.38	2.02	1.93
18	17.5	2.60	2.18	2.06
20	19.8	2.81	2.33	2.20

References

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2. Fitzpatrick Electric Supply Co., Muskegon, Michigan