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Destruction of Superconductivity by Current [1]

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A series of measurements was made of the return of resistance in superconducting wires when the current was increased up to and beyond the critical value. Wires of pure indium of three different diameters were used, and measurements were made on each wire at four different temperatures. The transition curves for a wire of given diameter were reproducible and were independent of temperature. Measurements on sections of wire 0.6 millimeter long gave substantially the same results as measurements on long wires. The fraction of the normal resistance restored by the critical current varied from 0.77 for a wire 0.36 millimeter in diameter to 0.85 for wires 0.11 millimeter in diameter. The classical formula predicts a value of 0.50. The results are discussed in the light of Landau's theory of the intermediate state, and it is shown that the classical value may be approached for wires of large diameter.

I. Introduction

The reappearance of electrical resistance as the current is increased in a superconductor was discovered by H. Kamerlingh Onnes [1] [2] in 1911. Since that time the phenomenon has been studied in several experimental investigations and has been considered from a theoretical point of view. Perhaps the most fruitful theoretical treatment was that given by Silsbee [2] in 1918 in which it was postulated that the magnetic field, associated with the current in a superconductor, is responsible for the restoration of resistance. That is, resistance reappears when the magnetic field reaches a critical value, regardless of whether the field is applied externally or is caused by the current in the conductor. This became known as the Silsbee hypothesis and has been verified in numerous experiments. Silsbee also reported a theoretical treatment suggested by Langevin, which described the resistance as a function of the current in a cylindrical wire as the current is increased up to, and beyond, the critical value. It was predicted that when the current reached the critical value the resistance would rise suddenly to one-half the normal value, and, as the current was further increased, the resistance would rise more slowly, approaching normal resistance asymptotically. The mathematical expression for the resistance was not included in Silsbee's paper, but F. London, in a similar analysis [3], gives the result,

$$R=\frac{R_n}{2}\left[1+\sqrt{1-\left(\frac{I_c}{I}\right)^2}\right],$$

where R is the resistance of the wire carrying the current, I; R_n is the normal resistance measured just above the transition temperature; and I_c is the current that will produce the critical magnetic field at the surface of the wire.

In this analysis the stable state of the conductor, carrying a current a little greater than I_c, is pictured as consisting of an outer shell of normally resistive metal surrounding an inner core of metal in the intermediate state, in which the magnetic field due to the current is exactly critical. Since at critical magnetic field the metal can be either superconducting or normally resistive, it is assumed that the intermediate core consists of layers of superconducting material separated by layers of resistive material, and that the thickness of the layers is a function of the radius such that the current will be distributed so as to maintain the critical value of the magnetic field throughout the core. This calls for a current density inversely proportional to the radius. At the critical value of the current the intermediate core extends to the surface of the wire and, as the current is increased above the critical value, the diameter of the intermediate core shrinks, causing a rise in the measured resistance.

[1] Supported by the Office of Naval Research, Contract NA-onr 12-48.
[2] Figures in brackets indicate the literature references at the end of this paper.

More recent experimental and theoretical investigations (see section VI) suggest that the simple theory just outlined will not account for all the results, because the distribution of normal and superconducting regions is restricted by the surface energy of the boundaries. Thus the pattern of superconducting and normal regions, which satisfies the conditions described above, may be inconsistent with the surface energy requirements.

It is the relation between current and resistance that is the subject of the present investigation. With one exception, the published experimental data give very little information concerning the shape of the transition curve. The exception is a paper by Shubnikov and Alexejevski [4] who found that the critical current caused the sudden reappearance of about 0.8 of the normal resistance in a tin wire immersed in helium II. Because of the marked discrepancy between this result and that predicted by the simple theory, it was considered worth while in the present work to make measurements on wires of different diameters and to conduct the experiments in such a way that the effects of heating by the current could be judged. Measurements were also made on short sections of wire to see if the results obtained on long wires were indicative of a fundamental behavior or were merely averages of more random effects in different parts of the wire.

II. Characteristics of the Specimens

The indium wires used for these experiments were extruded at room temperature through steel dies. A spectrochemical analysis of the indium showed the major impurity to be iron of the order of 0.1 weight percent. The superconducting elements, lead, tin, and thallium were present in amounts less than 0.01 percent. Mercury was not detected. Table 1 is a list of the dimensions of the specimens, their resistances at room temperature and the ratios of resistances just above the transition temperature to the resistance at room temperature. Specimen 1a, a duplicate of 1, was included because this fine wire was so fragile that it was feared there would be deformation when the specimens were mounted. Actually both specimens behaved almost identically, so results are given only for specimen 1.

TABLE 1. *Characteristics of the specimens*

Specimen	Diameter	Length	$R_{300°K}$	$\frac{R_{3.5°K}}{R_{300°K}}$
	mm	*mm*	*w*	
1	0.106	47	0.50	0.0013
1a	.106	47	.50	.0013
2	.286	47	.068	.0012
3	.357	47	.042	.0009
4 (section 1)	.106	0.57	.0059	.0013
4 (section 2)	.106	.63	.0065	.0013

III. Apparatus and Procedure

The cryostat used for this work consisted of a soda-glass Dewar flask for the liquid helium 6-cm inside diameter, 26 cm deep, in a brass jacket immersed in liquid hydrogen. The Pyrex Dewar containing the liquid hydrogen was also enclosed in a copper case, and this was immersed in liquid air. The liquid helium was produced with a separate Simon-type expansion liquefier provided with a transfer siphon so that the liquid helium could be delivered directly into the cryostat during the expansion. The helium produced in a single expansion, 200 to 300 cm, was so well-protected against heat leak in the cryostat that measurements could be taken for 24 hours or more.

The 47-mm specimens 1, 2, and 3 were mounted horizontally on a frame of mica and wood and were supported by the current and potential leads at each end, so that each specimen was in complete contact with the liquid-helium bath. The current and potential leads consisted of short lengths of indium welded to the specimen proper. The current leads, of greater cross section than the specimen, connected to lead (Pb) wires about 40 cm long, which were coiled in the liquid helium bath. The wires leading out of the bath were No. 37 AWG copper. The lengths of superconducting lead interposed between the copper wires and the specimen prevented heat developed in the copper from warming the specimens. The horizontal position of the specimens insured uniformity of temperature along the length.

Specimen 4 was a short length of indium wire provided with several potential taps spaced about 0.6 mm apart. The problem of obtaining close spacing of potential taps without seriously distorting the indium wire was solved by making two grids, each consisting of five separate parallel platinum wires 0.07 mm in diameter strung on a mica frame and spaced about 1.2 mm apart. The indium wire was laid across one of the grids perpendicular to the platinum wires, and the other grid was placed on top so that the platinum wires made contact with the indium on alternate sides at intervals of about 0.6 mm, thus making 10 potential taps. However, spurious potentials appeared between some of the potential leads when no current was flowing, so not all of the taps were usable. An examination of the specimen under the microscope showed a slight bending of the indium wire, 15 or 20 deg, where the platinum taps made contact, but the sections between the contacts were straight. This specimen was mounted in the cryostat with the indium wire in a vertical position.

The diameters of the indium wires were measured with a traveling microscope, using a bright field. The method was checked by making measurements on other wires of hard metal, which could be measured independently with micrometer calipers. The accuracy of the method was estimated to be about 0.001 mm. The wires were of circular cross section, as evidenced by the fact that different orientations showed the same diameter. Under certain types of lighting, very fine grooves could be seen on the surface of the wires, probably caused by imperfections in the dies. These were estimated to be of the order of 0.001 mm deep.

Current was supplied to the specimens by a 60-v battery through a bank of rheostats arranged for fine adjustment. The specimen currents and potentials were measured with a Wenner potentiometer. For very small potentials the potentiometer setting was left at zero, and measurements were made by means of galvanometer deflections, the sensitivity being of the order of 0.01 μv. Temperatures were determined by measuring the vapor pressure of the bath with a mercury manometer. No correction was made for the hydrostatic pressure of the helium above the specimen. Constant temperature was obtained by manual adjustment of a valve in the helium pumping line, according to the indications of a differential oil-manometer. The handle of the valve was a brass bar about 80 cm long, which permitted fine adjustment. A constantan heating coil at the bottom of the liquid helium bath, dissipating 0.005 to 0.01 w, caused some stirring of the liquid and improved the constancy and uniformity of temperature. The temperature could be kept constant to about 1 or 2×10^{-4} deg for periods of 10 min. Changes in room temperature affecting the differential manometer caused slow drifts of bath temperature amounting to about 0.001 deg/hr. A constant uniform temperature could be achieved very quickly after reducing the pressure over the bath, but after increasing the pressure it was necessary to wait sometimes as long as 30 min before accurate observations could be made. The differential manometer was also used to measure small changes of temperature, such as those required in determining the normal temperature-transition curves of the specimens. All temperatures were computed by means of the vapor-pressure equation for helium I given by Lignac [5]:

$$\log p_{cm} = -4.7921T^{-1} + 0.00783T + 0.017601T^2 + 2.6730.$$

The earth's field was neutralized with a pair of Helmholtz coils, 46 cm in diameter, surrounding the cryostat with their axis parallel to the earth's field. Another pair of Helmholtz coils of mean diameter 24 cm were used to produce a known uniform vertical field, in the region occupied by the specimens, for experiments on the restoration of resistance by an externally applied field.

The measurements on specimens 1, 2, and 3, and occasionally 1a, consisted of determinations of the normal temperature transitions with small specimen currents, and transitions with increasing and decreasing specimen current at four different constant temperatures below the normal transition temperature. Transitions with increasing and decreasing specimen current were also determined for several sections of specimen 4. When it was found that there was no appreciable difference in the behavior of different sections of specimen 4, only the data on sections 1 and 2 were recorded. Using potential taps about 3 mm apart, measurements of the restoration of resistance by a longitudinal magnetic field were made at three different temperatures.

IV. Results

The normal transition curves for the three wires of different sizes are shown in figure 1. The specimen current for each wire was chosen to produce a potential at normal resistance of 1 to 2 μv, to give reasonable sensitivity for the resistance measurements. The displacement along the temperature axis of the curves for the larger wires carrying the heavier currents is no doubt caused by the magnetic field produced by the specimen current. The agreement of the three curves at the top of the transition suggests that this is the most reproducible part of the transition curve and should be considered the normal transition temperature. The value thus obtained, 3.409° K, is somewhat higher than the values in the literature for the normal transition temperature of indium. The steep slope of the transition at 2 ma is gratifying, because it shows that neither impurities nor the polycrystalline nature of the specimen were having much effect on the superconducting properties.

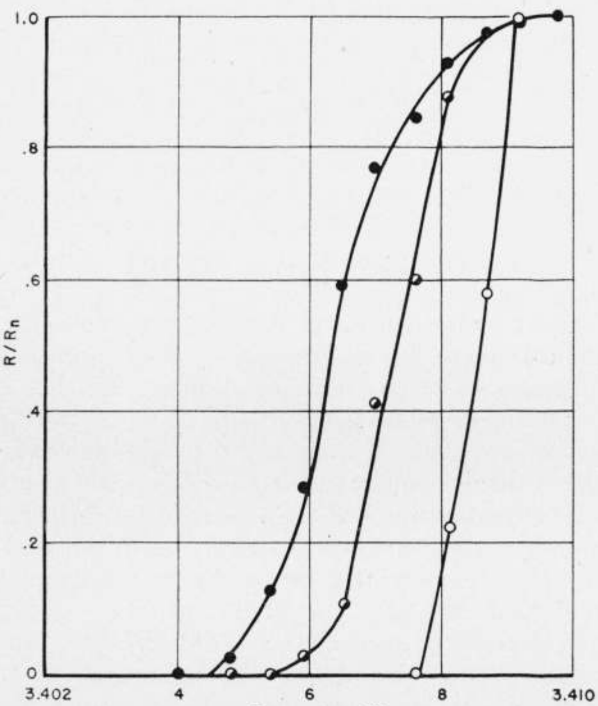

FIGURE 1. *Normal temperature-transitions of specimens 1, 2, and 3, with small measuring current.*

Specimen	Diameter	Measuring current
	mm	*ma*
○	0.106	2
◑	.286	23
●	.357	50

The transitions obtained by increasing the current through specimen 1 at four different constant temperatures are shown in figure 2, where the ratio R/R_n is plotted as a function of specimen current. R is the variable resistance of the specimen, and R_n is the value of R measured just above the normal transition temperature, or measured in an externally applied magnetic field of greater than critical intensity. It is seen that for each

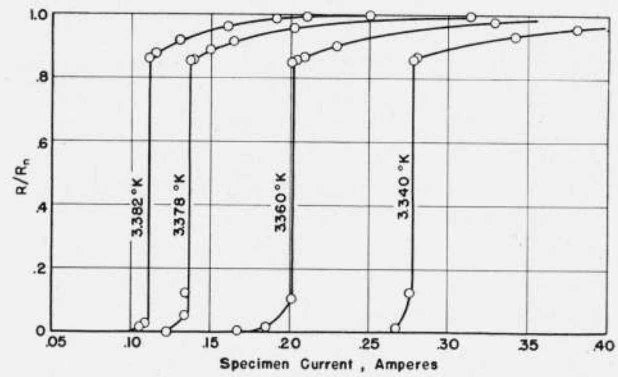

FIGURE 2. *Current-transitions of specimen 1 at four different constant temperatures.*

temperature there is a critical value of current that causes the resistance to rise suddenly to about 85 percent of the normal value. Further increase of current causes a gradual rise of resistance, the values of R/R_n approaching unity at high currents. The small resistance that appears at currents less than critical is probably caused by imperfections in the specimen. The results obtained at different temperatures can be correlated by plotting R/R_n as a function of I/I_c, where I is any value of the specimen current and I_c is the critical current. In such a plot all the data for a given specimen fall on a single curve. This is shown by the upper curve of figure 3, which includes the measurements made on specimen 1 at the highest and lowest temperatures. Data obtained at the lowest temperature on specimens 2 and 3 are also shown. Some of the current transition measurements were not plotted in figure 3, because the crowding of points would have caused confusion. Some of the observed points on specimens 1 and 3 were obtained with decreasing current as indicated by the arrowheads. At

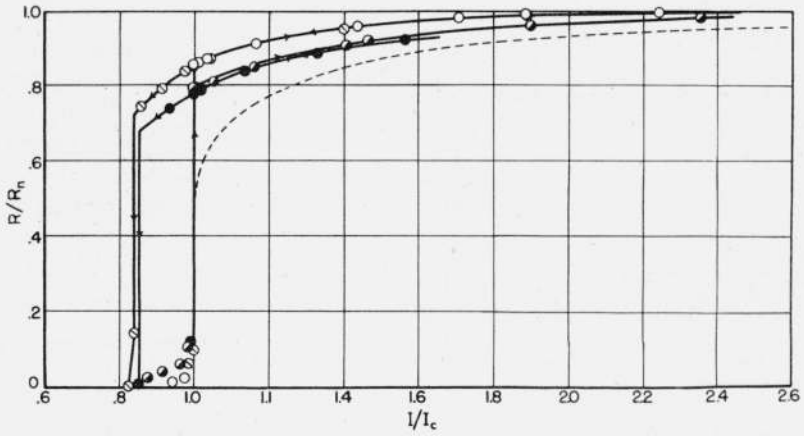

FIGURE 3. *Current-transitions of specimens 1, 2, and 3.*

The upper curve represents data on specimen 1 for the highest and lowest temperatures.

Specimen	Diameter	Temperature
	mm	*°K*
○, 1	0.106	3.3825
⊖, 1	.106	3.3401
◑, 2	.286	3.3410
●, 3	.357	3.3403

currents greater than critical, the resistance was the same for increasing and decreasing currents, but when the current was reduced below the critical value there was hysteresis, the resistance remaining large until the current was about 85 percent of the critical value. However, the value of current at which the drop in resistance occurred was by no means as definite as the critical current at which the rise of resistance occurred; and, as will be seen later, some specimens showed no hysteresis. The theoretical curve shown by the dotted line is a plot of the equation given in the introduction.

Table 2 is a summary of the current-transition measurements on specimens 1, 2, and 3. R_c is the value of R at the top of the sudden rise of resistance. The last column gives values of the critical field, $H_c=4I_c/10d$, where I_c is the critical current in amperes and d is the diameter of the specimen in centimeters.

The current-transition data obtained at 3.340° K on the short sections of specimen 4 are shown in figure 4. The solid curve is the same as the upper curve of figure 3, representing the data on the long specimen of equal diameter. The deviations of the observed points from the curve appear to be random and of such magnitude that they can be attributed to experimental error. The obviously poor accuracy resulted from the very low resistance of the sections measured. For these short sections there was little or no hysteresis when the current was reduced, the resistance dropping almost to zero as the current fell below the critical value.

TABLE 2. *Summary of the current-transition data on the 47-mm specimens*

Specimen	Diameter	Temperature	Critical current, I_c	R_c/R_n	Critical field computed from I_c
	mm	*°K*	*ma*		*Oersteds*
1	0.106	3.3825	115.0	0.860	4.34
		3.3778	142.2	.853	5.37
		3.3603	207.4	.848	7.83
		3.3401	283.9	.855	10.71
2	0.286	3.3835	202.1	.794	4.09
		3.3779	353.6	.791	4.95
		3.3613	533.7	.796	7.46
		3.3410	725.2	.799	10.14
3	0.357	3.3837	369.8	.777	4.14
		3.3780	440.8	.774	4.94
		3.3611	668.1	.779	7.49
		3.3403	935.6	.782	10.48

Figure 5 is a plot of the critical-field data. The solid circles represent measurements of the restoration of the resistance of specimen 4 by a longi-

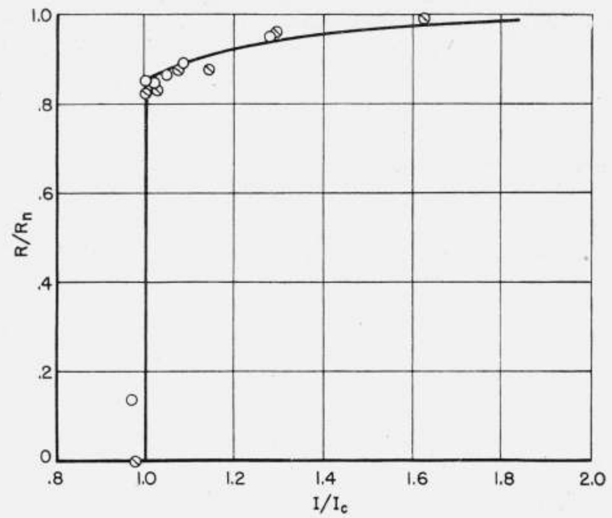

FIGURE 4. *Current-transitions of two sections of specimen 4 at 3.340° K.*

○, Section 1, length 0.63 mm; ⊖, section 2, length 0.57 mm.

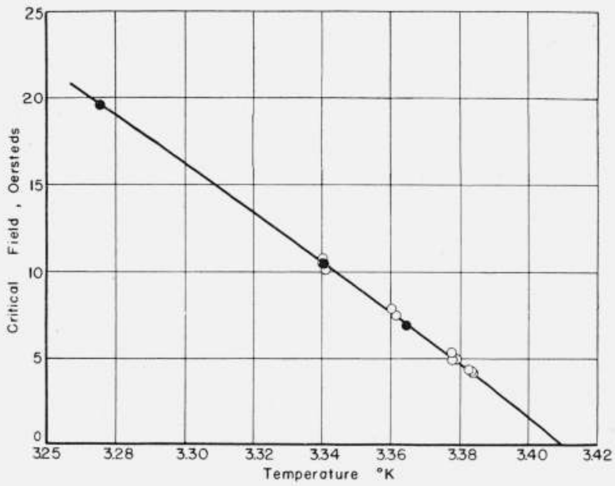

FIGURE 5. *Critical field measurements.*

Values of the critical external longitudinal field for specimen 4 are compared with values computed from critical currents. ●, Field applied externally; ○, field caused by critical current.

tudinal, externally applied magnetic field. The other circles represent the data on specimens 1, 2, and 3 given in table 2, where the critical field is computed from the critical current and the diameter of the wire. The agreement is excellent, the data accurately conforming with the Silsbee hypothesis and furnishing further evidence that the indium specimens behaved as ideal superconductors. Also, the curve through the data passes through the normal-transition temperature, 3.409° K, obtained independently (see fig. 1). As the data were distributed over a temperature range of only 0.14 deg, it was not considered worth while to use an analytical expression to fit the curve. Attempts to measure the critical field by applying it transversely were not very successful, because it was difficult to decide the value of the field at which the resistance reached the normal value. Also, the transition curves obtained were greatly dependent upon the specimen current, as may be seen in figure 6. These measurements were taken

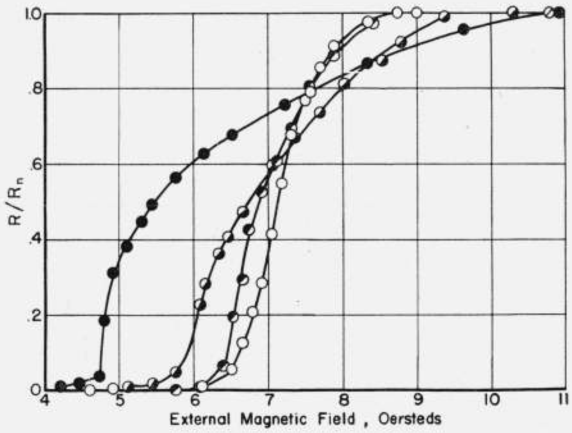

FIGURE 6. *Restoration of resistance by an externally applied transverse field*

○, 1 ma; ◐, 10 ma; ◑, 50 ma; ●, 100 ma.

on an earlier specimen of indium wire 0.106 mm in diameter, 10 cm long, in the shape of a W, mounted horizontally. The curves of figure 6 do not agree with similar measurements by De Haas, Voogd, and Jonker [6]; but, since they do not have a direct bearing on the present investigation, the matter was not pursued further.

V. Effect of Heat Produced by the Specimen Current

It is important to determine whether or not the temperature of the specimen is raised by the current. If there is appreciable heating, the temperature of the specimen may rise above the temperature of the bath when resistance appears. If this happened, part of the sudden rise of resistance could be attributed to a temperature change. The most direct evidence that heating effects are negligible is the fact that the initial rise of the resistance of a given specimen is independent of the critical current. This is seen in figure 2 and table 2. The power dissipated in a given wire varies by a factor of 6, without a significant difference in the initial rise of resistance. Actually this result might have been predicted because the power dissipated is very small, varying from a minimum of 7 $\mu w \, cm^{-2}$ for the largest wire at the highest temperature to a maximum of 270 $\mu w \, cm^{-2}$ for the smallest wire at the lowest temperature. The greatest power, 270 $\mu w \, cm^{-2}$, would cause the evolution of vapor bubbles in the liquid helium amounting to only about 2 mm^3 per second per cm^2 of surface at the prevailing pressure of 300 mm Hg; so it is not surprising that the temperature of the wires is practically unaffected.

VI. Discussion

Some conclusions that may be drawn concerning the data just presented are as follows:

1. The indium used accurately obeys the Silsbee hypothesis.

2. The results on the destruction of superconductivity by current are definite and reproducible.

3. For a wire of given size, R/R_n is a function of I/I_c only and is independent of temperature over the range covered by the experiments.

4. If the intermediate state of the wire is assumed to consist of definite regions of normal and superconducting material, the experiments on the short sections of specimen 4 show that the structure is fine grained compared with a length of 0.6 mm.

5. The value of R/R_n at critical current is a rather weak function of the diameter of the wire and is smaller for the larger wires.

6. For the wires used in these experiments the fraction of the normal resistance, restored by current equal to or greater than the critical current, is considerably larger than is predicted by the theory of Langevin.

London [7] has suggested that the cause of the discrepancy between the results of the present experiments and those predicted by the theory lies in the nature of the intermediate state. He [8, 9] describes the intermediate state as consisting of finite regions of normally resistive material interspersed among other regions of superconducting material. The size and shape of these regions are influenced, not only by such considerations as were the basis of the analysis given by Silsbee, but also by the surface energy [10] of the boundaries separating superconducting and normal metal. Landau [11, 12, 13], in extending the theory, made predictions as to the sizes of the regions; and Meshkovsky and Shalnikov [14] have made measurements of the magnetic field distribution in the intermediate state for massive tin hemispheres, finding regions of normal and superconducting metal of the order of 1 mm in thickness in the monocrystalline specimens. Shoenberg [15] discusses similar effects in considering the problem of the restoration of resistance in superconducting cylinders by a transverse magnetic field. As far as is known, there has been no theoretical treatment based on Landau's theory for the restoration of resistance by current.

It is probable that the distribution of normal and superconducting regions required by the simple theory is inconsistent with the surface energy requirements. For example, the extremely thin regions of normal metal near the center of the wire, separating other regions that are superconducting, may be energetically invalid, and a minimum thickness may exist. This would make a big difference in the resistance of a fine wire in the intermediate state, but for very large wires the effect would not be so important. To furnish support for this idea, an attempt was made to find an empirical relation between the wire diameter and the resistance, R_c, at critical current, which would be consistent with the observations and would give the value $R_c/R_n=\frac{1}{2}$ for very large wires. Also it seems reasonable that such a relation should yield the value, $R_c/R_n=1$ for very fine wires. A relation that satisfies these conditions and fits the data very well is

$$\ln\left(\frac{2R_c}{R_n}-1\right)=-\sqrt{d}.$$

A plot of this function is shown in figure 7. The

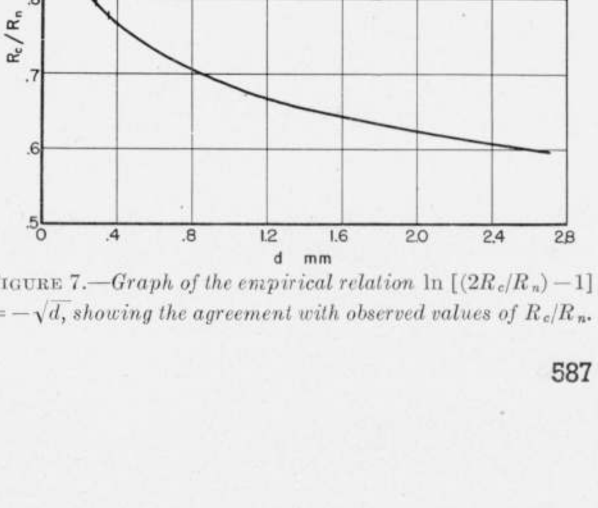

FIGURE 7.—*Graph of the empirical relation* $\ln[(2R_c/R_n)-1]=-\sqrt{d}$, *showing the agreement with observed values of* R_c/R_n.

curve represents the mathematical expression, and the short vertical lines represent the four observations on each of the three specimens 1, 2, and 3, as given in table 2.

It is recognized that the meager data furnish very flimsy support for the empirical relation. The real object in obtaining the equation was to demonstrate that the data are not in disagreement with the idea that the value $R_c/R_n = \frac{1}{2}$ may be approached with specimens of large diameter. Measurements on much larger wires would be required to establish experimentally a relation that could be accepted with confidence. If the relation given is approximately correct, the wire should have a diameter of 2.6 mm, or about seven times the diameter of the largest wire used in the present experiments, to give a value of 0.6 for R_c/R_n. This would call for specimen currents an order of magnitude greater than those used for specimens 2 and 3. The experimental arrangement used in this investigation did not permit the use of such large currents.

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