1948

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Recommended Citation

Holland, Chester Ray, "Hysteresis loss of supermalloy at different temperatures" (1948). *Masters Theses*. 4868.
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HYSTERESIS LOSS OF SUPERMALLOY
AT DIFFERENT TEMPERATURES

BY

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A

THESIS

submitted to the faculty of the
SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI
in partial fulfillment of the work required for the
Degree of
MASTER OF SCIENCE, PHYSICS MAJOR
Rolla, Missouri
1948

Approved by ______________________________
Associate Professor of Physics

ACKNOWLEDGMENT

The author wishes to express his appreciation to Dr. Z. V. Harvalik, Associate Professor of Physics at the Missouri School of Mines and Metallurgy for his suggestions and guidance throughout this investigation.

The cooperation received from the Western Electric and the Bell Telephone Laboratories in furnishing samples of their products for testing is deeply and sincerely appreciated.

May the author thank the following: Dr. L. E. Woodman, Dr. Z. V. Harvalik, and all members of the Department of Physics for their interest and assistance in this problem.

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INTRODUCTION

The object of this investigation was to measure the hysteresis loss of supermalloy at different temperatures, and to see if temperature had any effect on hysteresis loss and permeability. The maximum magnetizing current was held constant for all temperatures.

PRACTICAL APPLICATIONS OF HYSTERESIS

Hysteresis curves, along with the energy-product curves, the demagnetization curve, coercive force and residual induction, which are points on the curve or can be obtained easily from the curve, are of utmost importance in determining the characteristics of a specimen of iron or of any ferro-magnetic material. These points are used in determining the proper heat treatment, or in finding the stress or strain in steel. They are used in determining the best alloy for a certain job. For example; if you want a permanent magnet with certain characteristics for an ammeter, etc., by running hysteresis tests and by plotting energy-product curves, the best alloy for the specified job can be found. In this case a metal with a large energy-product curve, a large hysteresis loss along with a large coercive and residual force would be needed, and different tests on different alloys will determine the proper one. Whereas, for an alloy for the use of a core of a radio transformer quite different properties of the alloy are required as low hysteresis loss, high permeability, low coercive and residual force, and a small area within the energy-product curve, etc. Therefore, hysteresis tests would determine the best alloy for this use.

By comparison of hysteresis curves of steel which have been used excessively with standard specimens, any weakness or expected ruptures can be found.

Hysteresis losses along with eddy current losses cost the United States a lot of money, and anything that cuts down on this loss is of great importance. Lloyd(1) pointed out in 1910 that America alone had a financial loss of approximately ten million dollars annually, due to hysteresis loss. Therefore, a lot of money and research have been spent and are being spent to find means of cutting these losses down.

By studying the magnetization curves of various alloys, and in particular the effects on these curves,

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(1) Williams, S. R: Magnetic phenomena. McGraw-Hill Book Company, New York, 1931, p. 55.

when special heat treatments are applied to the metals, it has been possible to find alloys which will give certain specified magnetic properties. This is illustrated by the discovery of permalloy(2) which possesses a very high permeability for small magnetizing forces. Similarly, the discovery of perminvar(3) is another example of what can be accomplished along these lines for special uses.

DEFINITIONS

Oersted, in 1819, discovered that a magnetic field surrounds a wire carrying a current. He also found that the direction of the field about a current-carrying wire is tangentially perpendicular to the wire and that the intensity of the field diminishes in receding from the wire. The lines of force about an isolated wire are concentric with it, as can be proved by arranging it vertically and moving a suspended magnet or compass around it.

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(2) Arnold, H. D., and Elmen, G. W., Permalloy, an alloy of remarkable magnetic properties. Journal of Franklin Institute, Vol. 195, pp. 621-632, (1923).

(3) Elmen, G. W., Magnetic properties of perminvar. Journal of Franklin Institute, Vol. 206, pp. 317-338, (1928).

When an electric current is sent through a solenoid (a coil of wire wound uniformly in a long helix), the region inside and near the helix becomes a magnetic field. The magnetic field H at any point inside or near the helix may be determined from the strength of the current and the geometry of the helix. If a bar of any ferromagnetic material, e.g. a bar of iron, is placed inside the solenoid the iron becomes magnetized and the magnetic qualities of the region about the helix are changed. The magnetic flux through the region occupied by the bar is much greater than it was before the bar was placed there. This magnetic flux is referred to as "lines of induction", the expression "lines of force" being restricted to the flux when there is no magnetic substance present. The number of lines of induction per unit area is called the "magnetic induction" or "flux density" and is denoted by the symbol B.

Now suppose a ring of some magnetic material like mild steel is wound uniformly with a magnetizing coil of wire. Let the iron ring be first completely demagnetized as follows: An alternating current of, e.g. 50 cycles is passed through the magnetizing coil, P, having such a strength that the iron becomes magnetized to saturation. The current is then gradually reduced in strength by means of a resistance in series with the coil P, or alternatively by reducing the field strength of the alternator. After the current has been reduced to as low a value as possible in this way, the alternator is shut down and when it has completely come to rest, the coil P is disconnected. In this way the iron will have become thoroughly demagnetized.

If a small value of direct current be now passed through the exciting coil the curve connecting the magnetic induction B and the magnetic force H will take some such shape as Oa in Figure 1, that is, the values of B will increase at a moderate rate as the value of H increases.

When the value of the magnetization force H has reached a value of one or two oerstads, the curve rises much more rapidly as shown at ab. For high values of H, the curve bends back towards the H axis as shown at bc. If this given sample of iron is subjected to a uniformly increasing magnetizing field, the resulting flux density B does not vary linearly with the corresponding magnetizing field intensity H, but changes at a variable rate as shown by the curve Oabc in Figure 1.

The connection between B and H shown by the curve Oabc is the "magnetization curve" of the iron. When a sufficiently large value of the magnetizing field is reached, as specified by the point C, any further increase in the magnetizing field produces little or no increase in the flux density of the iron and the iron is said to be magnetically saturated.

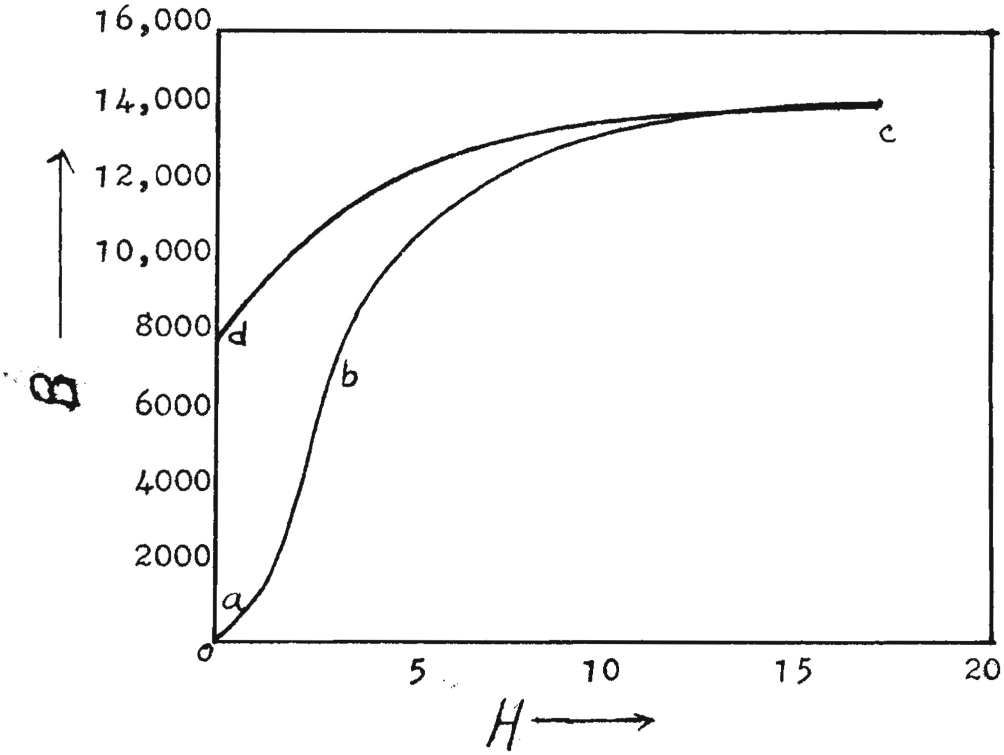

Figure 1.

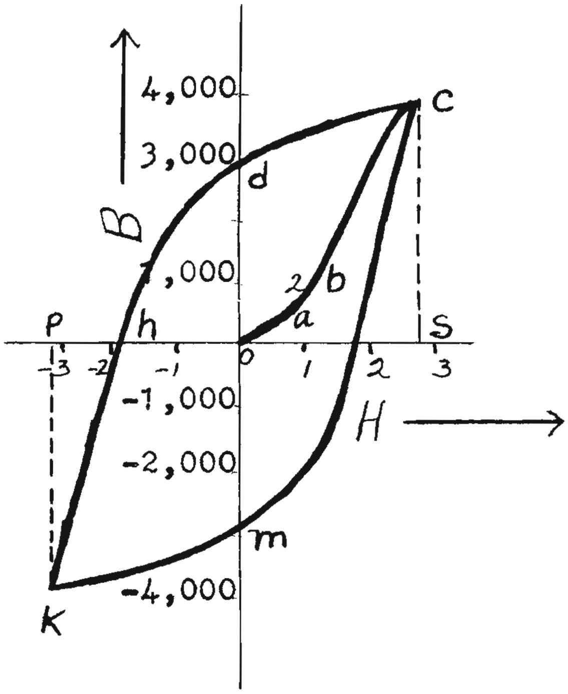

Figure 2.

If the magnetizing field is gradually reduced after the point of saturation is reached, the resulting flux density is given by the curve cd; at the point d the magnetizing field is zero but the flux density has a finite value represented by the ordinate Od. The value Od of the flux density for a piece of iron treated in this manner is called the "retentivity" of the iron.

Now referring to Figure 2 in which Oabc represents a magnetization curve and Od the retentivity. Suppose after having been reduced to zero, the magnetizing force is given a gradually increasing negative value. The corresponding values of the flux density B will be given by the curve dh, so that when B becomes zero, H has a negative value Oh. This value of H which is necessary to reduce the flux density to zero is termed the coercive force.

As H is still further increased in the negative direction, B becomes negative and the curve Hk is obtained such that, when the negative value of H, viz. Op, is the same as the maximum positive value of H, viz. Os, the maximum negative value of B is equal to the maximum positive value of B, that is Sc = pk.

If the negative value of H be now reduced to zero, the curve km is obtained, so that when H is zero, the flux density has a negative value Om. When H is increased in the positive direction, the curve mc is obtained, so that when H again reaches its former maximum positive value, the flux density B also attains its former maximum value. In this way a closed loop cdhkmc is obtained, and is known as the "hysteresis loop."

If the curve is followed around an a cyclical manner, i.e., the direction cdhkmc, it may be seen that at any point the resulting flux density B lags behind the magnetizing field H. Thus at any point d the magnetizing field is zero while the flux density has the finite value represented by Od. Again when the iron is in the state represented by the point h on the curve the magnetizing field has a negative value while the flux density is zero. This lagging of the flux density behind the magnetizing field is called "hysteresis".

The ratio of B to H at any time is called the magnetic permeability of the iron, or

$$\mu = \frac{B}{H}$$

The area of the hysteresis loop represents a definite amount of energy lost in performing the magnetic cycle and this loss is termed "hysteresis loss". The energy represented by the area of the hysteresis loop is dissipated in heat.

Warburg(4) showed that the energy loss due to

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(4) Williams, S. R., Magnetic phenomena. Mc-Graw Hill Book Company, Inc., New York, 1931, pp. 55-56.

hysteresis is equal to $\frac{1}{4\pi}$ times the area of the hysteresis loop, when H is in oersteds and B is in gauss, or

$$W = \frac{1}{4\pi}\int HdB \ \frac{\text{ergs}}{\text{cm}^3\text{-cycle}}$$

REVIEW OF THE LITERATURE

Hysteresis losses of different magnetic materials have been measured for some time. It was known that the energy required to magnetize a specimen was not entirely recoverable on removing the magnetizing force. The magnetization does not decrease to zero for zero field but an oppositely directed force must be applied to bring the intensity of magnetization back to zero.

Warburg(5) was the first to show that the area of a hysteresis loop was a measure of the amount of hysteresis loss during a magnetic cycle.

He proved later that the energy loss due to hysteresis was equal to

$$\frac{1}{4\pi}\ \text{(area of the hysteresis loop)}$$

or $$W_h = \frac{1}{4\pi}\oint HdB \ \frac{\text{ergs}}{\text{cm}^3 - \text{cycle}}$$

when B is in gauss and H is in oersteds.

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(5) Warburg, Freiburg, Wiedemann Annual, No. 8, Vol. 1, p. 1, Berlin, (1880).

In 1890 to 1891 Steinmetz(6) computed the energy loss in ergs per cubic centimeter per cycle for different values of maximum B (B_{max}) and plotted these values against the corresponding values of B_{max}. He expressed their relationship by an empirical equation of the form

$$W_v = \eta B_{max}^{k}$$

where k was given the value of 1.6, or

$$W_h = \eta B_{max}^{1.6}$$

Later experimental work showed that this equation was not rigorous. It was found that k varied considerably from 1.6 at high- and low-flux densities. The equation fits the experimental data best between the flux densities of 1,500 to 12,000 gausses. η is called the hysteretic constant or coefficient of hysteresis loss, which varies from one ferromagnetic body to another. It is a characteristic of the material. In some of the best silicon steels it is as low as 0.0006 and in some of the tungsten steels it has a value of 0.058.(7)

This law of Steinmetz has been extended to include eddy-current losses as well. For this purpose the equation of energy for the core loss takes the form

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(6) Steinmetz, Electrican, Vol. 27, p. 261 (1891).

(7) Williams, op. cit., p. 60.

$$W_c = W_h + W_e = \eta f B_{max}^{1.6} + E(f_x f B_{max} t)^2 \quad \frac{\text{ergs}}{\text{cm}^3\text{-sec.}}$$

f is the frequency of the alternating current applied to the specimen, E is the eddy-current constant which is a function of the specific resistance of the core, f_x is the form factor of the alternating wave of magnetic flux, η is the hysteresis constant and t is the thickness of the laminations.

Because the production, distribution, and control of electrical energy is so dependent upon a correct knowledge of the laws representing the relation between the electric current and magnetism, much labor has been spent in attempting to formulate a general law which shall express B as some function of H.

Frolich(8) in 1881 gave as a law the following expression:

$$B = \frac{H}{\alpha + \sigma H}$$

where $\sigma = \frac{1}{B_s}$ and α is a constant which measures the magnetic hardness.

Kennelly(9) introduced the reluctivity idea into Frolich's equation which gives it the form

$$\rho = \alpha + \sigma H$$

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(8) Williams, op. cit., p. 60.

(9) Kennelly, A. E., Transactions, American Institute of Electrical Engineers, Vol. 8, p. 485 (1891).

This has been called Kennelly's law. This law was developed independently by Kennelly and Fleming from the assumption that "permeability is proportional to the magnetizability"; that is,

$$\mu = a\ (S - B)$$

Kennelly recognized the fact that it is not the total induction B, but the intrinsic or ferric induction ($\beta' = B - H$) which approaches a saturation value (S) and developed the reluctivity relationship on that basis. Note that the ferric induction β', or B - H, is 4π times what is generally called intensity of magnetization or magnetic polarization. The symbol μ is here used for ferric permeability or $\frac{B'}{H}$ and is 4π times the magnetic susceptibility.

Starting from the equation

$$\mu = a\ (S - B)$$

it is possible by simple algebraic transformation to represent this equation by various forms.

Substituting $\frac{B'}{H}$ for μ and solving for B',

$$B' = \frac{HaS}{1 + aH}$$

If we put $\sigma = \frac{1}{S}$ and $\alpha = \frac{1}{aS}$ and substitute in the above equation, then

$$B' = \frac{H}{\alpha + \sigma H}$$

Since $B' = \frac{H}{\rho}$ we can see at once that

$$\rho = \alpha + \sigma H$$

This is Kennelly's law as usually stated. σ is the reciprocal of the saturation value and α is a constant which determines the rate of approach toward saturation.

Gokhale(10) discussed all of these laws and proposed one of his own. All these men labored under the same handicap that the constants have no physical significance.

All the laws have their limitations. Let us look at the magnetization curve and see where certain laws are best suited. The initial portion of the magnetization curve is not horizontal at the origin but has a definite slope called the initial permeability, μ_o, equal to $\frac{B}{H}$ for H = 0. Now for low inductions Lord Rayleigh(11) found that the relation

$$B = \mu_o H + aH^2$$

was obeyed and when the permeability μ is plotted against the field strength H, the points usually lie on a straight line corresponding to the equation

$$\mu = \mu_o + aH$$

The value of H at which the line begins to bend upward varies over wide limits from one material to another. In some abnormal materials such as the iron-silicon alloys

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(10) Gokhale, Paper presented at meeting of American Institute of Electrical Engineers, June 21-25, 1926.

(11) Bozarth, R. M., Magnetism. Reviews of Modern Physics, Vol. 19, pp. 29-86, January, 1947.

the curve first becomes convex upward before it begins to rise rapidly at higher values of H. Curves of this kind are used to determine the value of μ_o by extrapolating them to H = 0.

The upper portion of the magnetization curve bends over and approaches B_s. In high fields it is found that B approaches no definite limit but B - H does approach a limit, called the saturation induction or simply saturation, designated B_s. Since $B - H = 4\pi I$, I approaches the limit I_s, the saturation magnetization.

The upper part of the curve may be represented fairly well by O. Frolich's equation

$$B - H = \frac{H}{\alpha + \sigma H}$$

in which $\sigma = \frac{1}{B_s}$ and α is a constant which measures the magnetic hardness and is larger, the stronger the field necessary to attain any given fraction of saturation. When H is small enough to be neglected in comparison with B, this equation may be expressed in the equivalent form used by A. E. Kennelly:

$$\frac{1}{\mu} = \alpha + \sigma H$$

and so a linear relation is found when $\frac{1}{\mu}$ is plotted against H. From a graph of this kind one can easily determine the constants α and σ, and interpolate to find the value of μ for intermediate values of H. The slope of the line σ may be used to estimate the saturation induction ($\sigma = \frac{1}{B_s}$), but this method cannot be depended on for accuracy for in some materials such as iron the slope changes distinctly at inductions close to saturation. The term $\frac{1}{\mu}$ is termed the reluctivity.

Now let us discuss further the energy loss due to hysteresis. It has already been stated that the area enclosed by a hysteresis loop is proportional to the energy liberated as heat during one cycle of the loop.

Rayleigh derived the B^3 relationship at low inductions. He showed that the magnetization curve near the toe followed the equation:

$$B = \mu_o H + AH^2$$

and also that the hysteresis loop with tips at B_{max}, H_{max}, and $-B_{max}$, $-H_{max}$ was described by parabolic equations

$$B = \mu H + \left(\frac{a}{2}\right)\left(H_{max}^2 - H^2\right)$$

and

$$B = \mu H - \left(\frac{a}{2}\right)\left(H_{max}^2 - H^2\right)$$

for the upper and lower halves of the loop, respectively. (Here $\mu = \frac{B_{max}}{H_{max}}$) Measurements(12) have been made for values of B_{max} as low as 2 gausses, and only slight deviations from the Rayleigh form observed.

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(12) Bozarth, R. M., Magnetism. Reviews of modern physics, Vol. 19, pp. 29-86, (1947).

The area of a Rayleigh loop may be calculated from the above equations, and the corresponding hysteresis loss, expressed in $\frac{\text{ergs}}{\text{cm}^3 - \text{cycle}}$ is

$$W_h = \frac{a\, H^3_{max}}{3\pi} = \frac{a\, B^3_{max}}{3\pi \mu^3}$$

That temperature has an observable influence upon the magnetic properties of iron has been known from the time of Gilbert (1540-1603), who discovered that a needle, when heated red hot, is no longer attracted by the lodestone, but regains this property when the temperature has fallen. This fact was also noted by Canton and studied qualitatively by Saussure. The first, however, to attempt quantitative measurements was Coulomb (1736-1806), who observed the period of vibration of a heated magnetic needle in a field of known intensity.

At the beginning of the nineteenth century, the increasing refinement of instruments for studying the earth's field made it necessary to know the influence of temperature upon the deflections of the magnetometer needle. The first careful experiments were those of Christie who found that the highest temperature to which a magnet can be heated without sensible loss of magnetism is about 100°F., and that diminution of magnetic moment is not a linear function of the temperature, its rate of change increasing with the temperature. He also found that the moment of a magnet, when placed in a freezing mixture, is increased, returning to its original value when room temperature is restored.

Rowland in the years 1873-74, carried out a long series of experiments on iron, nickel, and cobalt, experimenting at two different temperatures, 5°C and 230°C, in the later part of his work. He was able to determine, however, that the susceptibility of iron and nickel in small fields is greater at high temperatures than low, while for large fields, just the reverse is true.

Baur, of Zurich confirmed the results of Rowland by studying iron as it cooled. He found, for small fields, that the rate of increase of permeability is greater for high temperatures than low, while as a critical temperature is approached, the permeability decreases very rapidly in all fields, becoming practically unity.

During the next ten years, the matter was taken up by Perkins, J. Trowbridge, Berson, Tomlinson and Hopkinson; by far the most important work being done by the last. Hopkinson used the ring method of Rowland, insulating the windings from each other by asbestos, and estimating temperatures by means of a platinum thermometer. He determined a very complete temperature series of magnetization curves for wrought iron, mild steel, hard steel, nickel and cobalt. In the case of wrought iron, he found that for small fields, e.g., 0.3

dyne, the temperature at which the rapid rise of permeability begins is about 600°C., then fell rapidly to unity. Mild steel showed essentially the same characteristics, except that the permeability had a smaller maximum, becoming unity at 735°C., while for hard steel, the decrease in the maximum was still more pronounced, magnetism disappearing at 690°C. Returning from higher temperatures, for wrought iron, magnetism reappeared at practically the same temperature at which it disappeared, but the steels showed a marked temperature lag which increased with carbon content.

Between the years 1890 and 1900 a great deal of work was done, and it will be possible here to briefly point out only the additions which were made to the results obtained by Hopkinson. We find a long list of names, the most important of which are the following: DuBois, Wilde, Rucher, LeChatelier, Curie, Fleming and Dewar, Morris, Fromme, Guilliaume, Dumont, Dumas, Asmond and Wills. The physical transformations which take place in iron were worked out with great detail during this decade by the metallurgists Osmond, Home, Roberts-Austin, Rozzeboom and others.

Of those mentioned above, Curie did perhaps the most important work. He studied not only iron, nickel and cobalt, but para- and dimagnetic substances, covering fields from 90 to 1,350, and temperatures from 15°C to 1400°C. He found that the magnetic transformation point for iron to be 760°C., somewhat lower than Hopkinson's value, and showed that the susceptibility does not become zero at this temperature, as previously supposed, but remains positive, and though small, decreases rapidly up to 950°C., then slowly to 1280°C., when an abrupt increase indicated another transformation point. The transformation near 750°C., was found to be not an abrupt, but a gradual change, depending upon the field, the curves showing the variation of susceptibility with temperature being similar in shape to Amagat's curves for the density of carbon dioxide near the critical point.

Fleming and Dewar, in 1896, studied the changes which were produced in the magnetic qualities of Swedish iron at low temperatures. In annealed specimens, they found the permeability in all fields less at low temperatures, while for unannealed and hardened iron, it increased as the temperature was lowered, the effect being greater with hardened iron. The hysteresis loss was independent of the temperature. More recently, Honda and Shimizu found for Swedish iron cooled in liquid air that the permeability and hysteresis loss decreased for small fields, but increased for large.

Earle M. Terry(13) found that for low fields, the permeability increased with the temperature for temperatures between 25°C. and 97°C. for unannealed specimens. He also found that the hysteresis loss, retentivity, and coercive force all decreased with a rise in temperature for these unannealed specimens. For the annealed specimens, he found that the permeability in low fields increased with a rise in temperature for temperatures between - 121°C. to + 102°C. But the hysteresis loss and the coercive force decreased with a rise in temperature in this range of temperatures. He found, however, the retentivity, Br, increased. His specimens were of electrolytic iron. He found as the temperature was reduced below standard room temperature, the permeability decreased for small fields but increased for large fields, this effect being greater after annealing. The hysteresis loss continually increased as the temperature was lowered, the rate of increase being greater after annealing. This was entirely at variance with Fleming's and Dewar's results on transformer iron, for they found no change in hysteresis loss at the temperature of liquid air. They also found the permeability to increase for all fields in the case of unannealed and hardened iron, which again was contrary to E. M. Terry.

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(13) Terry, E. M., The effect of temperature upon the magnetic properties of electrolytic iron, Physical Review, Vol. 30, 1910, pp. 133-160.

Hysteresis losses of different magnetic materials have been measured for some time, but as far as the literature is concerned, hysteresis losses of supermalloy at different temperatures have not been measured yet. It was, therefore, of interest to determine these constants of supermalloy, and this investigation was the topic of the thesis.

Bozorth(14) and his associates at the Bell Telephone Laboratories have measured the hysteresis loss of supermalloy as dependent on maximum induction (Wh Vs B_{max}), but not at different temperatures. They found that the hysteresis loss for supermalloy at B_{max} at 1000 gausses to be $\frac{0.4 \text{ ergs}}{\text{cm}^3 - \text{cycle}}$ and B_{max} at 5000 gausses to be 5 $\frac{\text{ergs}}{\text{cm}^3\text{-cycle}}$.

PRESENT THEORY EXPLAINING MAGNETIZATION AND HYSTERESIS CURVES(15)

It is generally conceded that the only known source of magnetic effects is electrons in motion. According

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(14) Bozorth, op. cit, pp. 29-86.

(15) Bozorth, R. M., Present status of ferromagnetic theory, Elec. Eng. 54, p. 1251 (1935).

(15) Bozorth, R. M., The physical basis of ferromagnetism. Bell System Tech. Journal, Vol. 19, p. 1, (1940).

to present theory, ferromagnetic effects are due to groups of electrons within a ferromagnetic material called "domains" and consisting of electrons spinning around their own axes. The magnetic axes of the spinning electrons in a single domain are held parallel to each other by mutual forces known as "exchange forces" so that each domain behaves as a single unit. The domains are in effect current-turns and so account for the magnetomotive forces inherent in ferromagnetic materials.

In the unmagnetized condition the domains are so oriented with respect to each other that the net magnetic force is zero in any direction. Under the influence of a magnetic field, e.g., applied by means of an external electric current, the magnetic axes of the domains tend to be oriented more or less in the direction of the applied field, so that their effect is added to that of the applied field.

The density due to the combined effect of the applied field and the domains is the magnetic induction B and the effect due to the orientation of the domains is the intrinsic induction Bi where $Bi = 4\pi J$, where J is the intensity of magnetization, $B = 4\pi J + H$ or $B = Bi + H$.

Now in the part of the magnetization curve Oa, Figure 2, B is proportional to H and if the current is broken B will return to zero. This is explained by saying that the axes of the electrons within the domain are deflected slightly but the exchange forces within the domains pull the axes back in the original position when the field is released. Now as more and more field is applied, more and more of the electrons within the domain orient themselves in the direction of applied field. This all takes place along the steep part, marked (2) from a to b of Figure 2 of the magnetization curve. Now as the iron becomes saturated, the axes of the domain shift and a further increase in H produces a small increase in B. This can be explained again by the equation $B = 4\pi J + H$ where at saturation the $4\pi J$ or intrinsic induction becomes a constant which for iron this constant is equal to (according to Wall(16)) 21,000 lines per square centimeter, and the equation becomes $B = 21{,}000 + H$. If, after saturation is reached, the field is reduced to zero, the part of the curve from saturation to the residual force is explained by saying that the domains themselves shift back to their position previous to saturation, but the axes of the electrons within the domains are still oriented. At $H = 0$, our equation becomes $B = B_1 = 4\pi J$. During the demagnetization part

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(16) Wall, T. F., Applied magnetism, Van Nostrand Company, New York, p. 31 (1927).

of the curve, the reverse of the magnetization takes place except the electrons do not quite go back to original position and at $B = 0$ we have $0 = H + 4\pi J$ and $H = 4\pi J$ where the field is equal and opposite to the intrinsic induction.

The energy loss due to hysteresis is heat causing a slight temperature change which may be calculated according to Joules' law.

Work = J X heat = ergs

where heat is expressed in calories and J is the mechanical equivalent of heat, J = 4.2 Joules per calorie.

DERIVATIONS

An electric current through a conductor is always accompanied by a magnetic field in the region surrounding the conductor. A magnetic pole placed in this field will be acted upon by a force.

Laplace(17) assumed that the magnetic field strength dH due to a current I through a short element of length dS is proportional directly to that length and to the strength of the current, and inversely to the square of the perpendicular distance from dS. He expressed this relation in the formula

$$dH = K \frac{IdS}{l^2} \qquad (1)$$

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(17) Gilbert, N. E., Electricity and magnetism, MacMillan Company, New York, pp. 93, 147, 163 (1932)

The unit of current strength is so chosen that $K = \frac{1}{10}$

Then, $$dH = \frac{IdS}{10\ l^2} \qquad (1)$$

This is an assumption which has always given correct results.

A conductor carrying a constant current is to be thought of as surrounded by a magnetic field, the lines of force being represented by concentric circles which lie in planes at right angles to the axis of the conductor. The direction of these lines is clockwise as one looks along the conductor in the direction in which the current flows, and the strength of the field, or the force on a unit pole, is determined by integrating the equation

$$dH = \frac{IdS}{10\ l^2}$$

Let us look at the magnetic field due to a long straight wire. The wire WW' in Figure 3 is assumed to be carrying a current I in a direction vertically downward, the magnetic force at P being toward the reader. Let the perpendicular distance from P to the wire be denoted by r, and let l denote the distance from P to the short

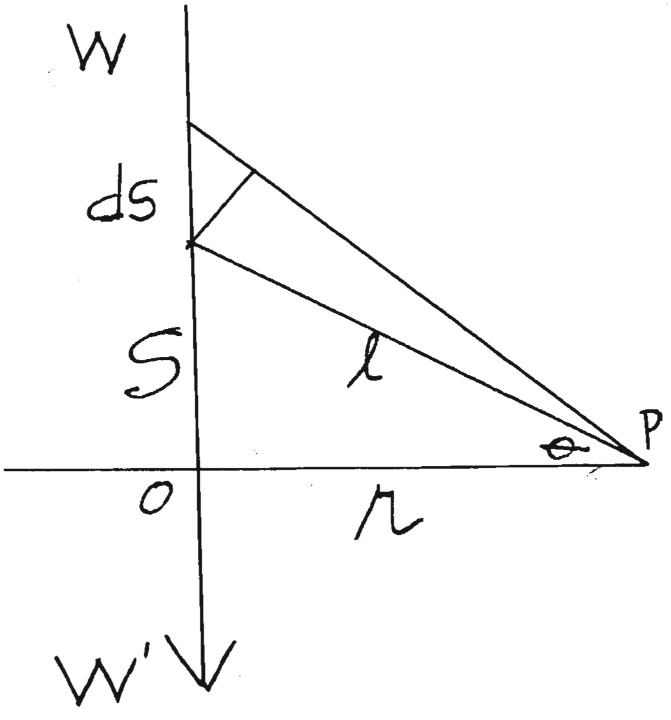

Figure 3

element of the wire dS. If this element were at right angles to l, the force dHp at P would be given by equation (1), but since the effective length of the element is dS cos θ, we have instead of this equation,

$$dH_p = \frac{IdS}{10\ l^2}\ \cos\theta \qquad (2)$$

The total field strength at P, due to that part of the wire above O, is given by integrating both sides of equation (2) between the limits of zero and infinity. The results must be doubled in order to include the effect of that part of the wire below O. Remembering that $\cos\theta = \frac{r}{l}$ and that I is a constant, we may write

$$H_p = \frac{2I}{10}\int_0^\infty \frac{r}{l^3}\,dS$$

Substituting for l, its value $(r^2 + S^2)^{\frac{1}{2}}$, we find

$$H_p = \frac{2Ir}{10}\int_0^\infty \frac{dS}{(r^2+S^2)^{3/2}} = \frac{2Ir}{10}\left[\frac{S}{r^2(r^2+S^2)^{\frac{1}{2}}}\right]_0^\infty$$

$$= \frac{2Ir}{10}\left[\frac{1}{r^2(\frac{r^2}{S^2}+1)^{\frac{1}{2}}}\right]_{S\,=\,\infty}$$

$$H_p = \frac{2Ir}{10}\cdot\frac{1}{r^2} = \frac{2I}{10r} \qquad (3)$$

The work done to carry a + 1 pole in a circle having a radius r around a wire carrying a current is force times distance. The force = $\frac{2I}{10r}$ dynes/unit pole, and the distance equals $2\pi r$.

$$\text{Work} = \frac{2I}{10r}\cdot 2\pi r = \frac{4\pi I}{10}$$

For any radius (r), work is $\frac{4\pi I}{10}$ ergs.

Since the radius disappears from the result, the work required is found to be independent of the path, and would be the same for any closed path around the conductor, whether circular or not. If a coil had n turns

$$\text{Work} = \frac{4\pi NI}{10} \text{ ergs} \qquad (4)$$

Now suppose we have a toroid, a ring of circular cross section wound uniformly with a layer or layers of wire, the work done is given by this equation

$$\text{Work} = \frac{4\pi NI}{10} \qquad (5)$$

around the median line of the toroid, or, the work = Hl, where H = field intensity and l = length of the median line.

$$Hl = \frac{4\pi NI}{10}$$

$$H = \frac{4\pi NI}{10l} \qquad (7)$$

In this investigation, Supermalloy, the hysteresis curve of which is to be determined, is in the form of a ring. Two dependent coils are wound around the sample. One winding, having N_1 turns of No. 26 wire, carries the primary magnetizing current I. The magnetizing field H due to a current I in this coil is given by

$$H = \frac{4\pi N_1 I}{10\ l} \qquad (8)$$

where l is the length of the coil, here the mean circumference of the ring. If H is measured in oersteds, then I must be measured in amperes. For a given ring and primary coil the quantity $\frac{4\pi N_1}{10\,l}$ is a constant. Thus it follows from equation (8) that the magnetizing field H is proportional to the magnetizing current I, or

$$H = C_1 I \qquad (9)$$

where C_1 is the constant $\frac{4\pi N_1}{10\,l}$.

This equation (9) is one of the working equations of this investigation.

A second coil with N_2 turns, called the secondary, is wound around the ring and is connected through a resistance to a ballistic galvanometer. This coil and ballistic galvanometer measure the change in flux density of Supermalloy due to changes in the magnetizing field. A change in the magnetizing current I produces a corresponding change in the magnetizing field H, and this effects some change in the flux density of the ring. Suppose a change ΔB occurs in the flux density of the Supermalloy ring. The change in the flux $\Delta\phi$ is $A \cdot \Delta B$ where A is the cross-sectional area of the ring. This flux change induces an electromotive force E in the secondary coil as given by

$$E = N_2 \frac{\Delta\phi}{\Delta t} \qquad (10)$$

where Δt is the time in which the flux changes, $\Delta\phi$ takes place. Thus

$$E = N_2 A \frac{\Delta B}{\Delta t} \qquad (11)$$

If E is to be expressed in volts when B is expressed in gausses, then the right hand member of equation (11) must be divided by 10^8, since 1 volt is equal to 10^8 abvolts. Thus

$$E \text{ (volts)} = \frac{AN_2}{10^8} \cdot \frac{\Delta B}{\Delta t} \qquad (12)$$

If the total resistance in the secondary circuit is R', then the induced current in the secondary circuit is

$$i = \frac{AN_2}{10^8 R'} \cdot \frac{\Delta B}{\Delta t} \qquad (12)$$

when R' is measured in ohms and ΔB in gausses, then i is in amperes. This induced current i lasts for the time Δt, the time in which the flux change takes place. The charge Q which flows around the secondary circuit due to this flux change is given by

$$Q = i\Delta t = \frac{AN_2}{10^8 R'} \cdot \frac{\Delta B}{\Delta t} \cdot \Delta t = \frac{AN_2}{10^8 R'} \Delta B \qquad (14)$$

If the charge flows through a ballistic galvanometer, the deflection of the galvanometer coil as measured by a reflected beam of light on a scale is proportional to the charge. Thus

$$Q = Kd \qquad (15)$$

where d is the deflection on the scale due to a charge Q and K is the charge sensitivity of the ballistic galvanometer. Substituting Kd for Q in equation (14), it follows that a change in flux density ΔB in the ring produces a throw d where

$$\Delta B = \frac{10^8 R' K}{AN_2} \cdot d \qquad (16)$$

Since the quantity $\frac{10^8 R'K}{AN_2}$ is a constant for a particular circuit, it follows from equation (16) that the deflection d on the galvanometer scale is proportional to the change in flux density ΔB; that is,

$$\Delta B = C_2 d \qquad (17)$$

where C_2 is the constant $\frac{10^8 R'K}{AN_2}$. A change in the magnetizing field, which from equation (9) is proportional to the change in the primary current I, produces a change in the magnetic flux density of the ring. This in turn is, from Equation (17), proportional to the throw of the ballistic galvanometer connected to the secondary coil wound around the Supermalloy ring.

If it is desired to obtain the absolute values of the flux density changes in place of the ballistic galvanometer throws, it is necessary to calibrate the galvanometer. This may be done by inserting permanently a known mutual inductance in series with the ballistic galvanometer and the secondary coil wound on the ring. The resistance of the galvanometer, previously called R', now also includes the resistance of the secondary of the mutual inductance. When a current I_M is sent through the primary of the mutual inductance, the flux through the mutual inductance coils is given by

$$\Phi = M I_M \, 10^8 \qquad (18)$$

where M is the mutual inductance of the two coils. If M is in henries and I_M in amperes, then ϕ is in maxwells. When the current I_M is broken, the change in flux through the coils is MI_M, and an electromotive force and current are induced in the secondary. The average induced electromotive force in volts is given by

$$E = \frac{MI_M}{\Delta t} \qquad (19)$$

where Δt is the time taken for the flux to be reduced to zero. The current in the secondary and galvanometer circuit is

$$I_s = \frac{MI_M}{R' \Delta t} \qquad (20)$$

and the quantity of electricity flowing through the galvanometer is

$$Q = I_s \Delta t = \frac{MI_M}{R'} \qquad (21)$$

If this discharge of electricity through the galvanometer causes a deflection d_M, then

$$Q = Kd_M \qquad (22)$$

where K is the charge sensitivity of the galvanometer which depends not only on the characteristics of the galvanometer, but also on the resistance R' of the secondary circuit. From equations (21) and (22) it follows that

$$K = \frac{MI_M}{d_M R'} \qquad (23)$$

Upon substitution of this value of K in equation (16)

$$\Delta B = \frac{MI_M\ 10^8}{AN_2\ d_M} \cdot d = C_3 d \qquad (24)$$

where $C_3 = \dfrac{MI_M\ 10^8}{AN_2 d_M}$.

Equation (9) is one of the working equations and equation (24) is the other working equation of this investigation.

DISCUSSION OF EXPERIMENT

(1) Preparation of Samples

The composition(18) of Supermalloy is about 79 per cent nickel, 5 per cent molybdenum, 15 per cent iron, and 0.5 per cent manganese. Impurities such as silicon, carbon, sulfur, etc., are lower than in most commercial alloys. Materials are melted in vacuum in an induction furnace of about 30 pounds capacity, and poured in helium or nitrogen at atmospheric pressure.

Ingots are hot and cold-rolled by commercial methods to any thickness down to 0.00025 inch. The tape is wound spirally to form taroidal specimens. When insulation is desired, a thin film of magnesia (MgO) is applied in carbon tetrachloride suspension so that a film of about 0.0005 inch in thickness is left on each side of the tape. Transformer cores are made in this manner. Heat treatment for annealing requires holding at 1300°C. for two to twelve hours in pure dry hydrogen, and then cooling from 600°C. to 300°C. at the rate of 1 to 2°C. per minute. The purity of the hydrogen must be very high.

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(18) Boothby, O. L., and Bozorth, R. M. A new magnetic material of high permeability. Journal of Applied Physics, Vol. 18, pp. 173-176, February, 1947.

Both annealed and unannealed specimens were used in this investigation. Both samples were insulated with magnesium oxide. The insulated specimens contain roughly 2 per cent by weight of magnesium oxide. These samples were in the form of a toroidal ring with two independent coils of which are wound around the sample.

These toroidal rings weighing approximately 80 gm. have a mean diameter of approximately 3.30 cm. with a cross-sectional area between 0.8 cm^2 to 0.9 cm^2. In calculating the cross-sectional area, the weight and a density of 8.74 was used.

One coil winding called the primary which consisted of twenty turns of fairly large copper wire was connected to the current source. The field intensity, H, is calculated according to equation (9) above, from the number of turns and the dimensions of the coil and the current indicated by the ammeter.

The other coil winding called the secondary which consisted of 252 turns of small copper wire was connected to a ballastic galvanometer. In the secondary circuit a mutual inductance, M, with an air core is provided for calibrating, and a switch for short circuiting the galvanometer.

When H is changed suddenly from one value to another, the resulting change in B induces a voltage in the secondary coil and causes a deflection on the galvanometer that is proportional to the change in B. Equation (24) was used to determine the change in B.

The Earth's magnetic field was neutralized by use of a Helmholtz coil. These coils consisted of five turns of large copper wire each, spaced 14 cm. apart, with a radius of 14 cm. These coils were mounted at an angle of 69.25° with the horizontal which was the Earth's magnetic inclination. These coils established, with a current of 1.695 amperes, a field of 0.573 oersteds, which was the magnetic field at Rolla, Missouri.

In order to keep the Supermalloy ring in a cyclic state and determine the points along the hysteresis curve a special switch was used. This switch was "Smith's Hysteresis Switch" sold by the Central Scientific Company. The Supermalloy ring is taken through a complete hysteresis cycle by moving the switch from position 2 on the right to position 2 on the left and returning to position 2 on the right. Repeating this operation several times puts the sample in a cyclic state. Since the resistance R_1 controls the maximum magnetizing current, the sample should be taken through several hysteresis cycles after any change in R_1. If the ring is in a cyclic state, it should be found that the sum of the galvanometer throws when the switch is moved from position 2 on the right to position 2 on the left should equal those obtained when the switch is moved back in reverse direction. Keeping the resistance R_1 fixed and changing the resistance R maintains the maximum magnetizing current I_2 but changes the current I, and thus gives other points on the curve.

A mutual inductance of 0.00123 henries was used so as to obtain absolute values of B. The primary of the mutual inductance was in series with a battery, ammeter, rheostat and switch. The secondary was in series with the galvanometer circuit all the time during the experiment.

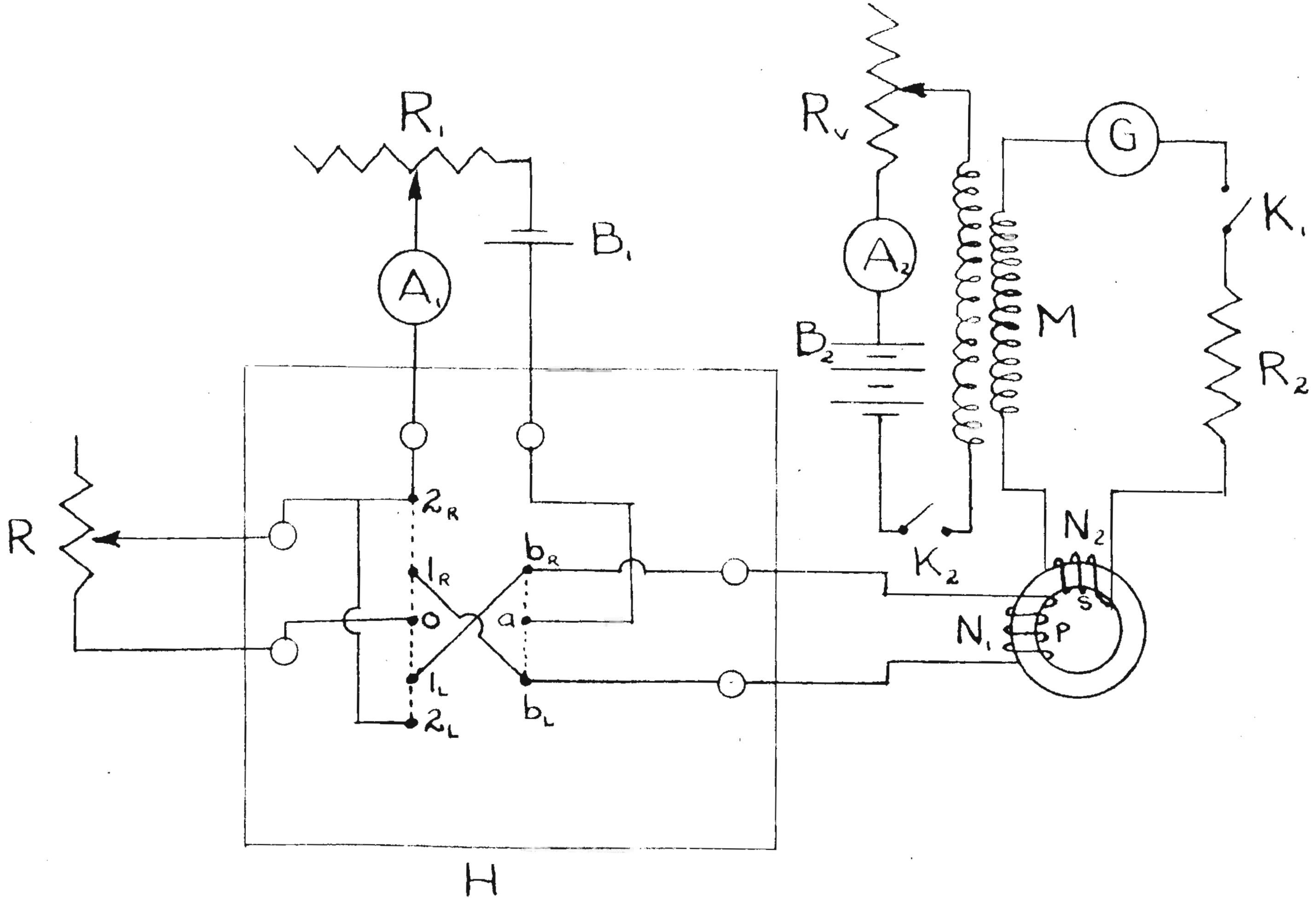

FIG. 4

The Magnetization Circuit.

Symbols for Figure 4:

G = ballistic galvanometer.

A_1 = ammeter to measure magnetizing current.

A_2 = ammeter to measure inductance current.

R_1 = fixed resistance for each hysteresis loop.

R = variable resistance.

M = mutual inductance.

S = secondary coil on supermalloy ring.

P = primary coil on supermalloy ring.

B_1 = battery furnishing the magnetizing current.

B_2 = battery for current in mutual inductance.

K_1 = galvanometer switch.

K_2 = mutual inductance switch.

H = Smith's hysteresis switch

2R, 1R, 1L, 2L, etc. = positions on hysteresis switch.

R_2 = resistance in series with galvanometer.

A Leeds and Northrup ballistic galvanometer with a charge sensitivity of 0.0017 microcoulombs per millimeter deflection on a scale 50 cm. away was used. This galvanometer had a period of 23.1 sec.

A Simpson electric microammeter, with a scale range of 0-500 microamperes, was used to measure the magnetizing current for sample No. 1, Supermalloy. A Weston ammeter with a range 0-1.5 amperes, was used to measure the magnetizing current for sample No. 2.

During this investigation the maximum magnetizing current was held constant throughout, but the temperature of the samples were varied from about -73°C. to about 100°C. To obtain different temperatures from room temperature to 100°C. hot water baths were used. A steam bath was used for temperature of 100°C. For temperatures down to 0°C. cold water baths were used. A mixture of ice and water was used to obtain a temperature of 0°C. For temperatures below 0°C., dry ice and acetone were used. A mixture of dry ice and acetone was used to obtain a temperature of -73°C.

During this experiment the samples were in a neutralized Earth's magnetic field.

Equation (9) was one of the working equations. This equation determined the field strength.

$$H = \frac{4\pi N_1 I}{10\ l} \qquad (9)$$

where N_1 = number of turns on primary of supermalloy ring.

I = current through this primary in amperes.

l = length of coil of ring = the mean circumference of the ring.

Then H = field intensity in oersteds.

For sample No. 1 annealed and for No. 1 annealed "aged"(19)

N_1 = 20 turns

l = 10.46 cm.

For samples No. 1 annealed and No. 1 annealed "aged",

$$H = \frac{4\pi \times 20}{10 \times 10.367} I = 2.42 \; I \text{ oersteds}$$

For sample No. 2 unannealed

$$H = \frac{4\pi \times 20}{10 \times 10.46} I = 2.40 \; I$$

Equation (24) is the other working equation:

$$\Delta B = \frac{M I_M \, 10^8}{A N_2 \, d_M} \, d \qquad (24)$$

where M = mutual inductance = 0.00123 henries

I_M = current in the solenoids(M)
inductance in amperes

A = cross-sectional area of Supermalloy ring in cm^2

N_2 = number of turns in secondary on ring = 252 turns.

d_M = galvanometer deflection by current through inductance coil M in centimeters.

d = galvanometer deflection by current from secondary on supermalloy ring in centimeters.

Then, ΔB is in gauss.

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(19) Sample No. 1 annealed was "aged" in this way; it was subjected to the extreme temperature ranges of -73°C. to + 100°C. in rapid succession.

For samples No. 1 annealed and No. 1 annealed "aged",

$$\Delta B = \frac{MI_M \, 10^8}{AN_2 d_M} \cdot d = \frac{0.00123 \times 0.750 \times 10^8}{0.811 \times 252 \times .975} \, d$$

$$\Delta B = 463 \, d$$

For sample No. 2 unannealed,

$$\Delta B = \frac{0.00123 \times 0.750 \times 10^8}{0.894 \times 252 \times 0.975} \quad d = 420 \, d.$$

TABLE NO. 1

Magnetizing current in micro-amperes	Temperature in degrees Centigrade							
+ 4000	-73	-62	-50	-36	+ 2°	+ 29	+ 60	+ 99°C.
3700	.03	.06	.04	.05	.11	---	.06	---
3500	.05	.08	.09	.11	.19	.20	.12	---
3000	.10	.12	.15	.19	.39	.32	.24	.21
2500	.15	.20	.22	---	.59	---	.38	.35
2000	.20	.26	.31	.40	.82	.69	.52	.48
1500	.25	.34	.37	.49	1.08	.90	.70	.62
1000	.31	.41	.48	.58	1.34	1.12	.90	.81
500	.36	.46	.55	.73	1.62	1.42	1.09	1.00
0	.42	.55	.64	.82	1.95	1.70	1.34	1.22
500	.06	.08	.09	.11	.35	..35	.29	.29
1000	.11	.16	.20	.24	.78	.80	.68	.65
1500	.18	.26	.30	.37	1.24	1.38	1.19	1.12
2000	.25	.32	.41	.55	1.79	2.08	1.86	1.81
2500	.31	.41	.52	---	2.42	----	2.82	2.90
3000	.37	.50	.60	.89	3.13	4.20	4.30	4.94
3500	.45	.58	.72	1.00	3.88	5.30	6.61	----
3700	.52	.62	.77	1.10	4.12	----	7.71	----
-4000	.53	.69	.86	1.17	4.44	6.56	8.36	9.79

Galvanometer deflections in centimeters

Sample No. 1 - Annealed Supermalloy

In order to get the above deflections the magnetization current was changed from + 4000 microamperes to 3700 microamperes, + 4000 to 3500 microamperes, + 4000 to 3000 microamperes and so on down to 0 microamperes. Then the current was changed from 0 to -500 microamperes, 0 to -1000 microamperes and so on down from 0 to -4000 microamperes.

TABLE NO. 2

Magnetizing current in micro-amperes	Temperature in degrees Centigrade							
-4000	-73	-62	-50	-36	+ 2	+ 29	+ 60	+ 99°C.
3700	.03	.03	.05	.06	.10	---	.06	---
3500	.04	.05	.07	.09	.17	.18	.10	---
3000	.09	.11	.14	.19	.35	.28	.21	.19
2500	.13	.19	.21	---	.57	---	.34	.28
2000	.20	.26	.30	.39	.78	.61	.50	.40
1500	.25	.32	.37	.48	1.01	.82	.65	.54
1000	.29	.39	.46	.58	1.27	1.04	.82	.68
500	.34	.45	.56	.72	1.56	1.31	1.01	.85
0	.40	.51	.62	.82	1.87	1.57	1.24	1.04
500.	.05	.06	.08	.11	.33	.32	.29	.22
1000	.10	.12	.18	.22	.76	.77	.63	.52
1500	.17	.21	.27	.38	1.22	1.31	1.11	1.00
2000	.22	.30	.40	.55	1.78	2.02	1.78	1.61
2500	.30	.40	.50	---	2.44	----	2.72	2.55
3000	.36	.48	.61	.88	3.17	4.16	4.20	4.26
3500	.42	.58	.72	1.00	3.90	5.35	6.73	---
3700	.48	.60	.76	1.10	4.18	----	7.83	---
+4000	.49	.65	.83	1.18	4.49	6.69	8.46	10.12

Galvanometer deflections in
centimeters

Sample No. 1 annealed Supermalloy (continued)

In order to get the above deflections, the magnetizing current was changed from -4000 to -3700 microamperes, -4000 to -3500 microamperes, and so on down to zero. Then the current was changed from zero to + 500 microamperes, 0 to + 1000 microamperes and so on down to + 4000 microamperes.

TABLE NO. 3

Temperature in degrees Centigrade
From 4000 to 3700 - 4000 to 3500 etc.

Magnetizing current in micro-amperes

+ 4000	-72°	-61	-52	-42	-32	-20	-11°C.	+ 3°C.	15	29	40	60	80	99°C.
3700	.01	.01	.02	.02	.03	.02	.02	.05	.05	.05	.06	.05	.05	.05
3500	.02	.03	.04	.05	.04	.05	.06	.09	.10	.10	.10	.09	.08	.09
3000	.05	.07	.07	.09	.09	.10	.11	.18	.18	.20	.20	.19	.17	.15
2500	.08	.10	.11	.11	.13	.17	.17	.25	.27	.30	.29	.29	.25	.25
2000	.10	.12	.15	.16	.19	.22	.24	.33	.39	.40	.39	.38	.35	.34
1500	.12	.17	.20	.21	.25	.28	.31	.42	.49	.50	.51	.50	.46	.44
1000	.16	.20	.23	.26	.29	.32	.40	.53	.58	.60	.61	.61	.58	.56
500	.18	.23	.27	.31	.34	.38	.49	.64	.69	.72	.73	.74	.69	.69
0	.21	.26	.31	.35	.40	.45	.51	.74	.80	.85	.88	.86	.82	.81
500	.03	.03	.05	.03	.05	.06	.07	.10	.11	.12	.14	.13	.15	.16
1000	.05	.07	.08	.09	.09	.10	.13	.20	.23	.27	.29	.31	.32	.35
1500	.08	.10	.11	.13	.16	.18	.22	.34	.38	.42	.47	.51	.54	.61
2000	.10	.15	.16	.19	.22	.26	.31	.48	.50	.58	.63	.73	.81	.91
2500	.13	.19	.21	.25	.28	.32	.39	.59	.68	.79	.85	1.02	1.21	1.41
3000	.17	.22	.26	.31	.36	.41	.47	.72	.85	1.00	1.14	1.42	1.78	2.25
3500	.20	.25	.30	.38	.41	.49	.54	.88	1.01	1.25	1.51	1.96	2.55	3.29
3700	.21	.27	.32	.40	.44	.54	.57	.96	1.10	1.37	1.72	2.21	2.89	3.71
4000	.22	.29	.35	.41	.46	.55	.65	1.04	1.20	1.52	1.87	2.52	3.25	4.14

Galvanometer deflections in centimeters

Sample No. 1 annealed "aged" Supermalloy

In order to get the above deflections the magnetization current was changed from + 4000 microamperes to 3700 microamperes, + 4000 to 3500 microamperes, + 4000 to 3000 microamperes and so on down to 0 microamperes. Then the current was changed from 0 to -500 microamperes 0 to -1000 microamperes and so on down from 0 to -4000 microamperes.

TABLE NO. 4

		Temperature in degrees Centigrade													
	-4000	-72	-61	-52	-42	-32	-20	-11°C.	+ 3°C.	15	29	40	60	80	99°C.
Magnetizing Current in Micro-amperes	3700	.01	.01	.02	.02	.03	.04	.04	.05	.05	.04	.04	.04	.04	.04
	3500	.02	.02	.04	.04	.06	.07	.07	.08	.09	.08	.08	.08	.09	.08
	3000	.05	.07	.09	.10	.11	.11	.12	.16	.17	.18	.16	.17	.16	.16
	2500	.08	.10	.11	.14	.15	.18	.19	.22	.26	.25	.25	.23	.25	.22
	2000	.11	.12	.16	.17	.20	.23	.26	.32	.35	.35	.43	.35	.32	.32
	1500	.12	.16	.20	.21	.27	.30	.32	.40	.43	.45	.44	.44	.42	.41
	1000	.16	.20	.22	.26	.30	.35	.42	.50	.53	.55	.55	.55	.56	.52
	500	.18	.23	.26	.30	.35	.40	.50	.60	.65	.66	.67	.68	.66	.65
	0	.20	.26	.31	.35	.41	.48	.54	.69	.75	.77	.77	.77	.78	.77
	500	.03	.02	.02	.05	.05	.07	.08	.10	.10	.11	.11	.11	.14	.14
	1000	.06	.07	.09	.10	.11	.12	.16	.21	.23	.25	.27	.30	.31	.35
	1500	.09	.10	.11	.14	.19	.19	.22	.32	.37	.40	.43	.50	.56	.60
	2000	.10	.12	.18	.20	.22	.25	.31	.47	.50	.58	.61	.72	.81	.92
	2500	.13	.19	.20	.25	.30	.33	.39	.60	.69	.79	.86	1.04	1.25	1.44
	3000	.16	.20	.26	.31	.36	.40	.47	.75	.87	1.01	1.17	1.45	1.81	2.30
	3500	.19	.25	.30	.38	.42	.49	.52	.90	1.03	1.28	1.57	2.03	2.60	3.39
	3700	.21	.27	.33	.40	.46	.54	.56	.98	1.14	1.41	1.77	2.29	2.92	3.75
	+4000	.22	.28	.35	.44	.49	.55	.64	1.06	1.24	1.57	1.91	2.56	3.24	4.17

Galvanometer deflections in centimeters

Sample No. 1 Annealed "aged" Supermalloy

In order to get the above deflections the magnetizing current was changed from -4000 to -3700 microamperes, -4000 to -3500 microamperes, and so on down to zero. Then the current was changed from zero to + 500 microamperes, 0 to + 1000 microamperes and so on down to +4000 microamperes.

TABLE NO. 5

Magnetizing current in Amperes	Temperature in degrees Centigrade											
+1.50	-70	-61	-45	-27	-11	+ 1°C.	+14	27	40	60	80	99°
1.35	.03	.04	.02	.05	.05	.04	.06	.07	.06	.06	.05	.07
1.2	.10	.10	.09	.11	.11	.11	.12	.13	.12	.12	.12	.13
1.0	.18	.19	.19	.20	.20	.22	.21	.20	.21	.22	.21	.21
.9	.23	.23	.23	.25	.26	.27	.28	.28	.29	.28	.27	.28
.8	.28	.29	.28	.30	.31	.34	.32	.33	.33	.37	.32	.32
.7	.31	.35	.33	.34	.38	.38	.39	.39	.40	.40	.41	.40
.5	.45	.45	.47	.45	.50	.50	.51	.52	.53	.51	.52	.51
.4	---	---	.51	.50	.58	.60	.60	.58	.60	.62	.60	.60
.25	.60	.60	.62	.62	.69	.69	.70	.71	.74	.71	.72	.79
.10	.70	.71	.72	.73	.80	.86	.86	.85	.86	.83	.91	.96
.05	.75	.76	.78	.79	.85	.88	.87	.90	.87	.94	.98	1.00
.0	.83	.84	.85	.87	.95	.94	.96	.95	.95	.97	1.01	1.02
.05	.02	.03	.03	.03	.03	.04	.04	.06	.05	.06	.06	.02
.10	.06	.06	.07	.07	.09	.10	.10	.10	.10	.10	.10	.10
.25	.17	.18	.19	.19	.21	.25	.23	.28	.28	.28	.27	.29
.40	---	---	.31	.32	.36	.44	.42	.46	.49	.50	.49	.49
.50	.38	.41	.40	.44	.50	.56	.56	.61	.62	.65	.62	.64
.70	.65	.70	.73	.72	.80	.89	.88	.96	.99	1.04	1.01	1.08
.80	.78	.81	.80	.91	.99	1.09	1.08	1.18	1.20	1.28	1.26	1.32
.90	1.00	1.06	1.09	1.11	1.21	1.31	1.32	1.42	1.47	1.58	1.56	1.69
1.00	1.16	1.28	1.32	1.37	1.50	1.60	1.64	1.76	1.82	1.97	2.06	2.22
1.20	1.61	1.79	1.91	2.02	2.25	2.40	2.58	2.71	2.88	3.23	3.71	4.12
1.35	2.06	2.30	2.47	2.63	2.90	3.12	3.35	3.51	3.70	4.29	4.75	5.29
1.50	2.34	2.68	2.75	3.01	3.31	3.53	3.81	4.05	4.31	4.94	5.61	6.03

Sample No. 2 - Unannealed Supermalloy

The magnetization current was changed from 1.50 amperes to 1.35 amperes, 1.50 amperes to 1.2 amperes, 1.5 to 1.0 amperes, and so on down to zero amperes. Then the current was changed from zero to .05 amperes, 0 to 0.10 amperes, and so on down to -1.50 amperes.

TABLE NO. 6

Magnetizing current in Amperes -	Temperature in degrees Centigrade											
-1.50	-70	-61	-45	-27	-11	+ 1	+ 14	27	40	60	80	99°C
1.35	.07	.06	.06	.07	.06	.05	.06	.05	.06	.06	.07	.07
1.20	.13	.11	.11	.12	.11	.11	.10	.10	.12	.11	.14	.13
1.00	.20	.20	.20	.22	.21	.24	.22	.21	.23	.22	.23	.22
.90	.26	.27	.28	.28	.28	.30	.30	.29	.29	.29	.30	.30
.80	.32	.31	.33	.32	.31	.35	.35	.32	.35	.35	.38	.35
.70	.38	.37	.38	.40	.39	.39	.39	.39	.40	.41	.41	.42
.50	.50	.50	.50	.53	.52	.51	.51	.51	.52	.55	.58	.56
.40	---	---	.57	.59	.59	.60	.61	.60	.60	.61	.66	.65
.25	.68	.67	.68	.70	.70	.73	.72	.71	.75	.75	.80	.80
.10	.79	.78	.80	.82	.80	.86	.87	.87	.88	.89	.92	.96
.05	.83	.85	.87	.90	.88	.90	.89	.89	.90	.93	1.00	1.00
0	.91	.88	.92	.96	.96	.94	.96	.94	.96	.98	1.06	1.05
.05	.05	.04	.04	.04	.04	.04	.05	.05	.05	.05	.05	.04
.10	.09	.09	.09	.09	.09	.09	.09	.10	.09	.10	.10	.10
.25	.19	.19	.20	.22	.22	.26	.26	.27	.29	.29	.30	.30
.40	---	---	.33	.38	.38	.43	.43	.47	.48	.50	.49	.50
.50	.42	.44	.44	.50	.50	.58	.59	.61	.62	.65	.66	.68
.70	.72	.76	.79	.82	.82	.90	.92	.96	.99	1.04	1.06	1.10
.80	.90	.95	.96	.93	1.00	1.11	1.10	1.19	1.20	1.27	1.30	1.36
.90	1.05	1.12	1.16	1.18	1.20	1.35	1.29	1.42	1.49	1.58	1.61	1.72
1.00	1.13	1.34	1.39	1.49	1.58	1.65	1.71	1.79	1.83	1.99	2.11	2.30
1.20	1.70	1.87	2.00	2.12	2.33	2.48	2.65	2.75	2.92	3.29	3.83	4.22
1.35	2.07	2.32	2.47	2.59	2.94	3.19	3.38	3.53	3.74	4.28	4.82	5.32
+1.50	2.33	2.68	2.72	2.97	3.23	3.63	3.82	4.07	4.28	4.90	5.61	5.99

Sample No. 2 Unannealed Supermalloy

The magnetization current was changed from -1.50 amperes to 1.35 amperes, -1.5 amperes to 1.35 amperes, and so on down to zero. Then the current was changed from zero to 0.05 amperes, 0 to .10 amperes, 0 to .25 amperes, and so on down to + 1.50 amperes.

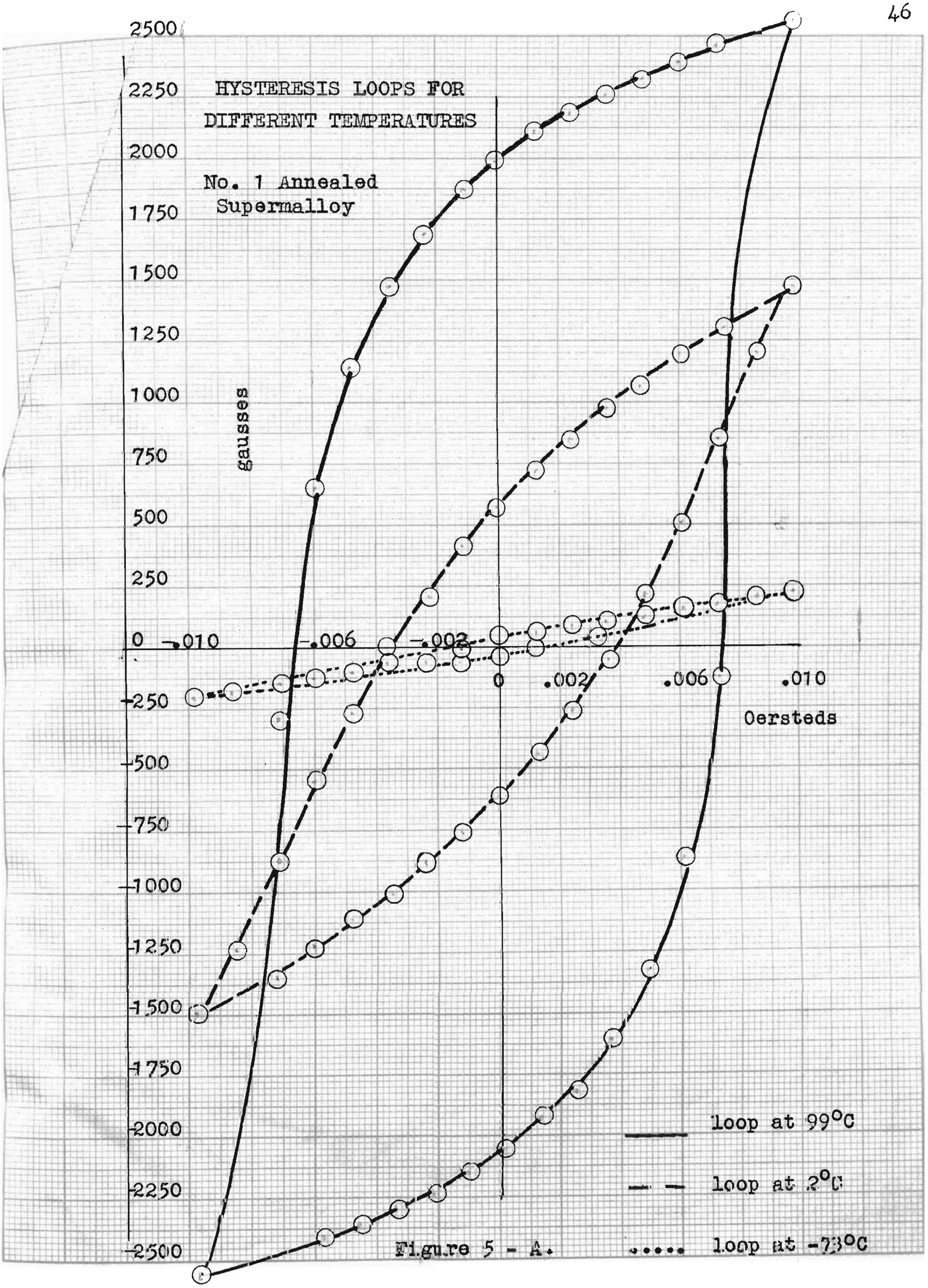

HYSTERESIS LOOPS FOR
DIFFERENT TEMPERATURES
No. 1 Annealed
Supermalloy
gausses
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-.010
-.006
-.002
0
.002
.006
.010
Oersteds
loop at 99°C
loop at 2°C
loop at -73°C

Figure 5 - A.

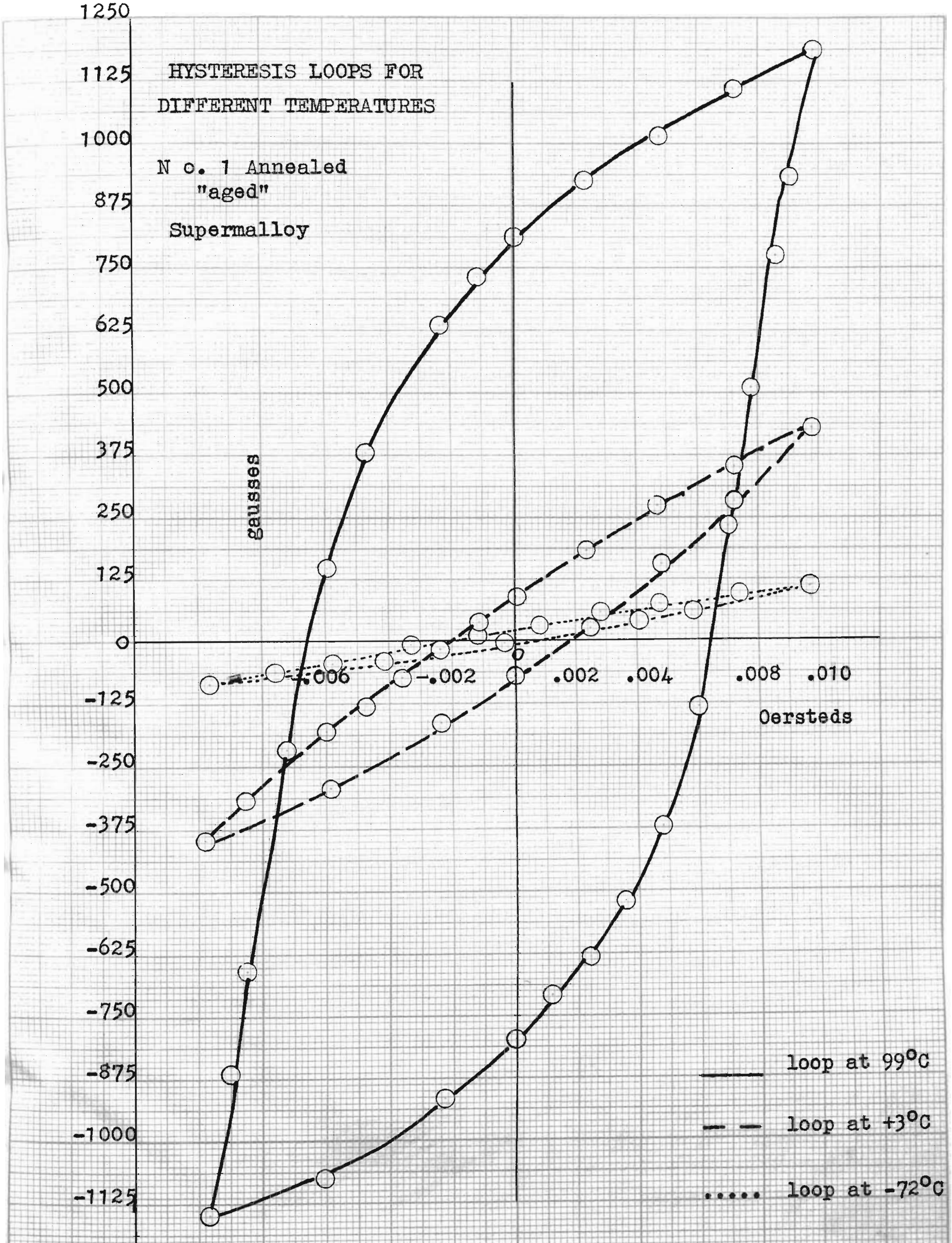

HYSTERESIS LOOPS FOR
DIFFERENT TEMPERATURES
N o. 1 Annealed
"aged"
Supermalloy
gausses
1250
1125
1000
875
750
625
500
375
250
125
0
-125
-250
-375
-500
-625
-750
-875
-1000
-1125
-.006
-.002
0
.002
.004
.008
.010
Oersteds
loop at 99°C
loop at +3°C
loop at -72°C

Figure 5 - B.

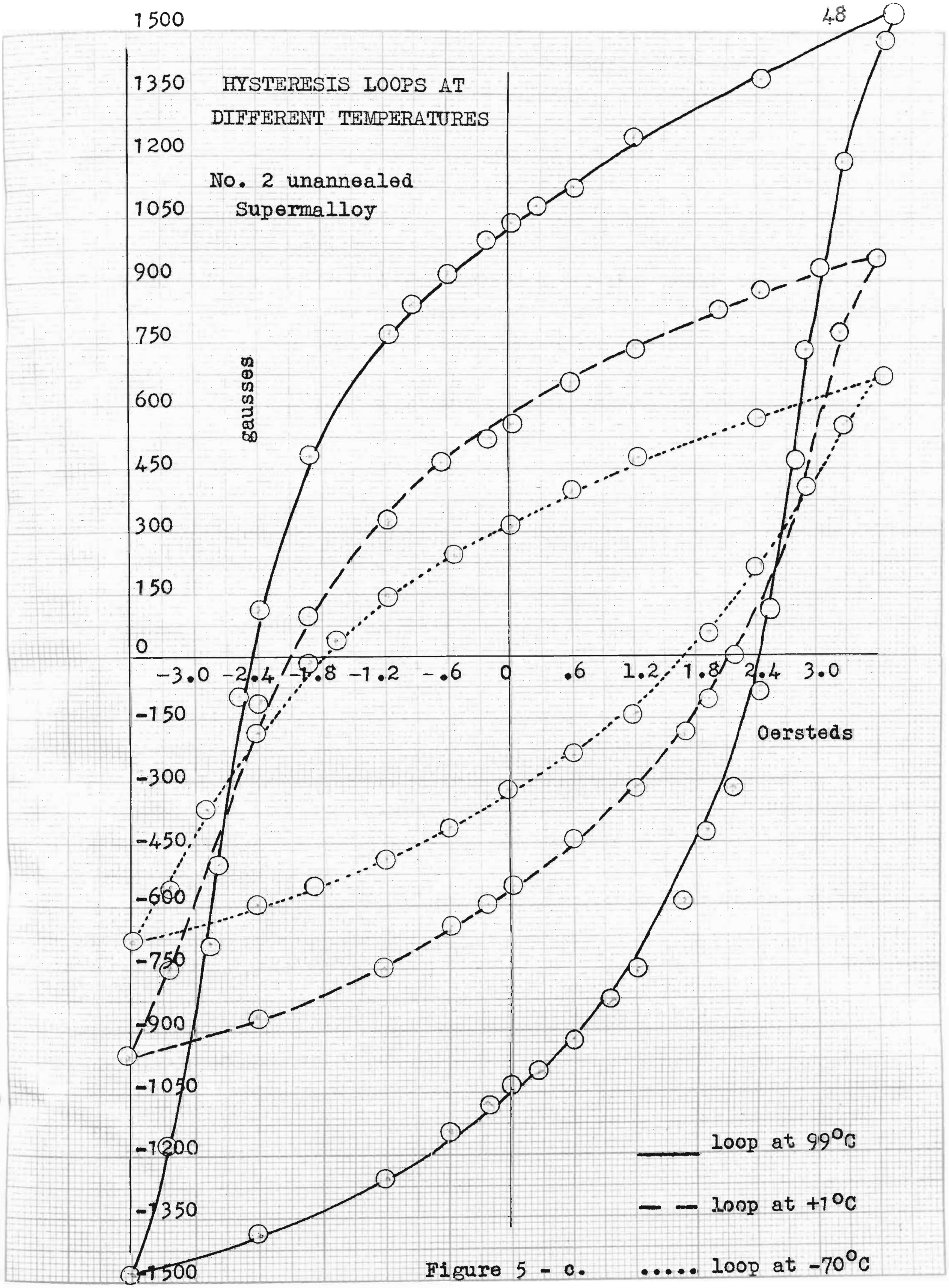

HYSTERESIS LOOPS AT DIFFERENT TEMPERATURES
No. 2 unannealed Supermalloy
gausses
1500
1350
1200
1050
900
750
600
450
300
150
0
-150
-300
-450
-600
-750
-900
-1050
-1200
-1350
-1500
-3.0
-2.4
-1.8
-1.2
-.6
0
.6
1.2
1.8
2.4
3.0
Oersteds
loop at 99°C
loop at +1°C
..... loop at -70°C

Figure 5 - c.

TABLE NO. 7

Maximum galvanometer deflections in centimeters as dependent on temperature.

Temperature in degrees Centigrade

	-73°	-62°	-50°	-36°	+ 2°	+ 29°	+ 60°	+ 99°
Annealed Supermalloy	0.90	1.21	1.48	2.00	6.37	8.26	9.70	11.08

	-72	-61	-52	-42	-32	-20	-11	+ 3°	15	29	40	60	80	99
Annealed "aged" Supermalloy	.42	.55	.65	.76	.88	1.01	1.17	1.76	2.00	2.36	2.71	3.35	4.07	4.95

	*70	-61	-45	-27	-11	+ 1	+ 14	27	40	60	80	99°
Unannealed Supermalloy	3.20	3.52	3.62	3.90	4.28	4.52	4.78	5.00	5.25	5.90	6.65	7.04

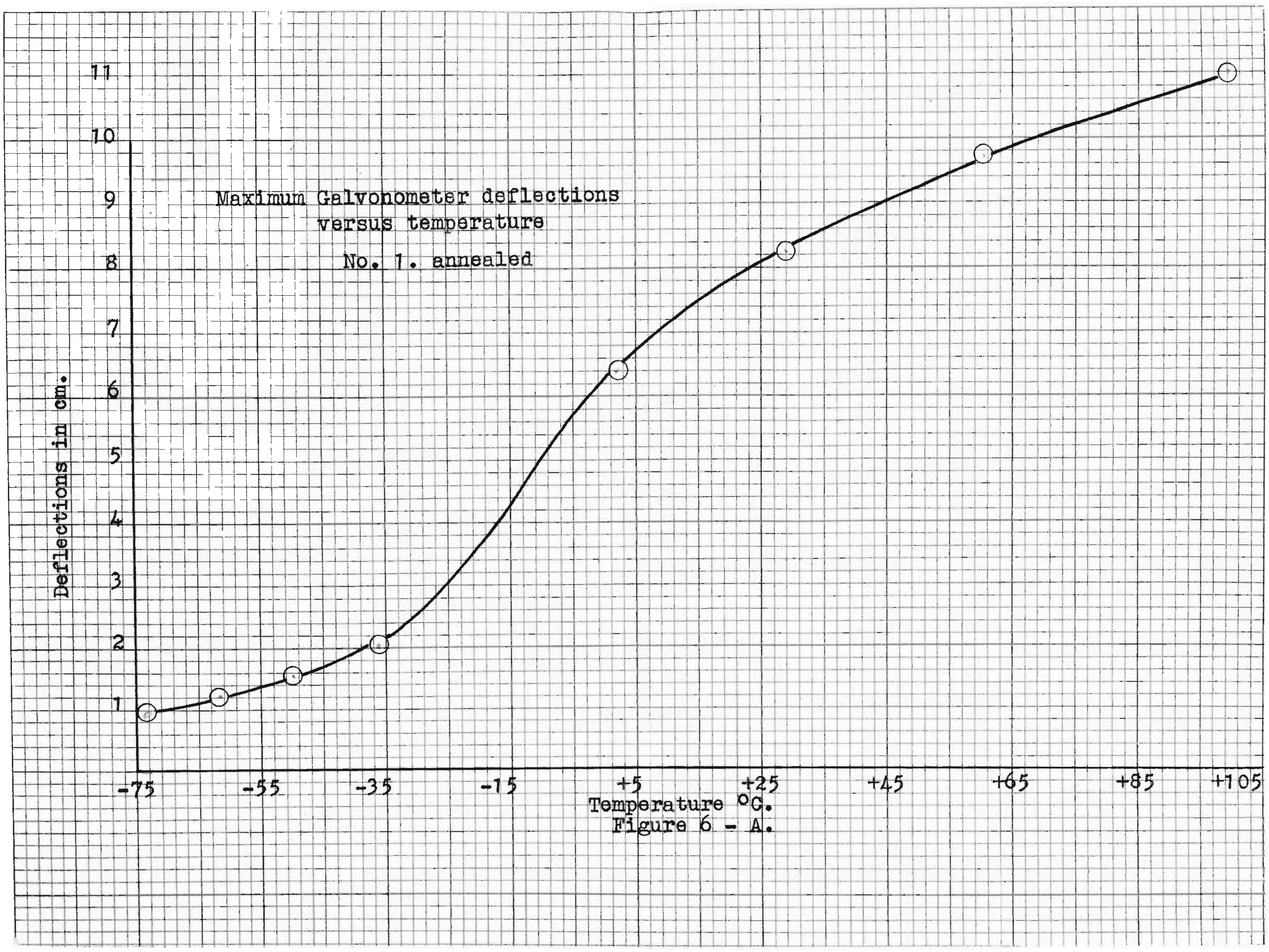
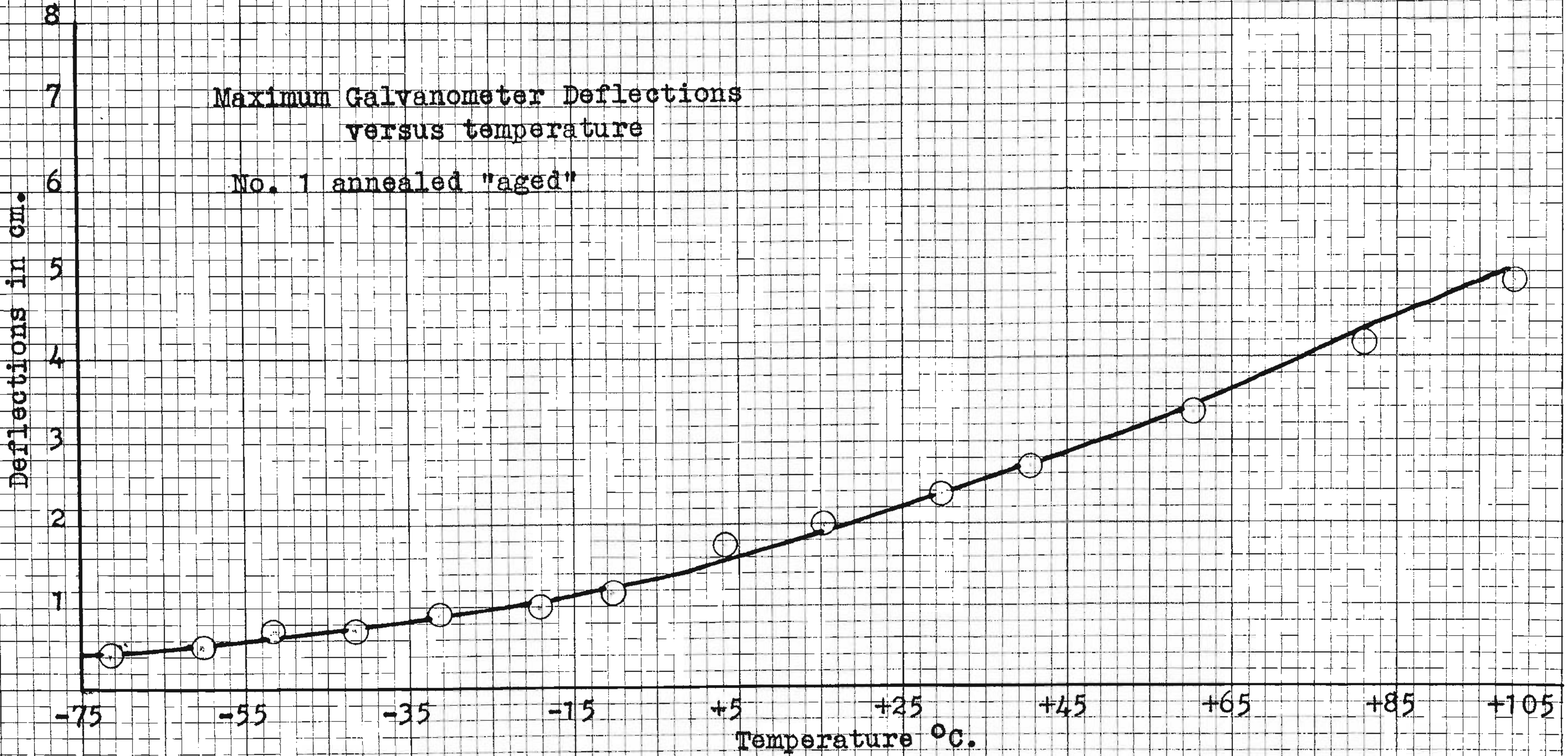

Maximum Galvonometer deflections
versus temperature
No. 1. annealed
Deflections in cm.
1
2
3
4
5
6
7
8
9
10
11
-75
-55
-35
-15
+5
+25
+45
+65
+85
+105
Temperature °C.

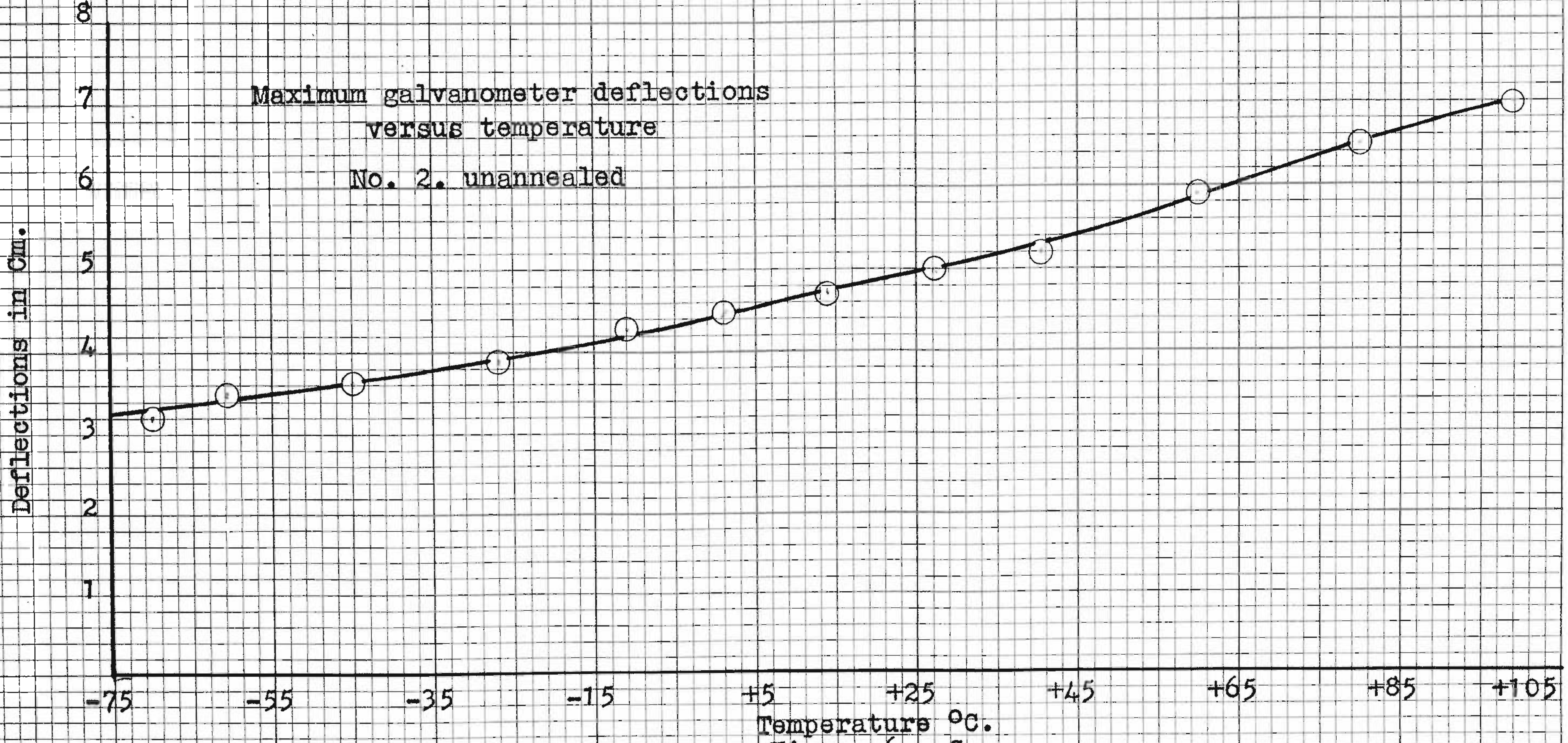
Figure 6 - A.



Maximum Galvanometer Deflections
versus temperature

No. 1 annealed "aged"

Figure 6 - B.



Maximum galvanometer deflections versus temperature

No. 2. unannealed

Figure 6 - C

TABLE NO. 8

Residual Magnetism, Br, in gausses as dependent on temperature.

Temperature in degrees Centigrade.

463 d

	-73°	-62	-50	-36	+ 2	+ 29	+ 60	99°
Annealed Supermalloy	18.5	32.4	43.1	80.6	568.6	1152.9	1648.3	2041.8

463 d

	-72°	-61	-52	-42	-32	-20	-11	+ 3	+15	+ 29	+ 40	+ 60	80	99
Annealed "aged" Supermalloy	4.2	6.5	9.3	16.7	18.1	18.5	27.8	53.7	107.9	168.1	247.2	398.2	569.5	779.2

420 d

	-70	-61	-45	-27	-11	+ 1	+ 14	+ 27	+ 40	+ 60	+80	+99
Unannealed Supermalloy	307.8	378	389.3	435.6	453.6	552.3	596.4	655.2	701.4	827.4	961.8	1044.8

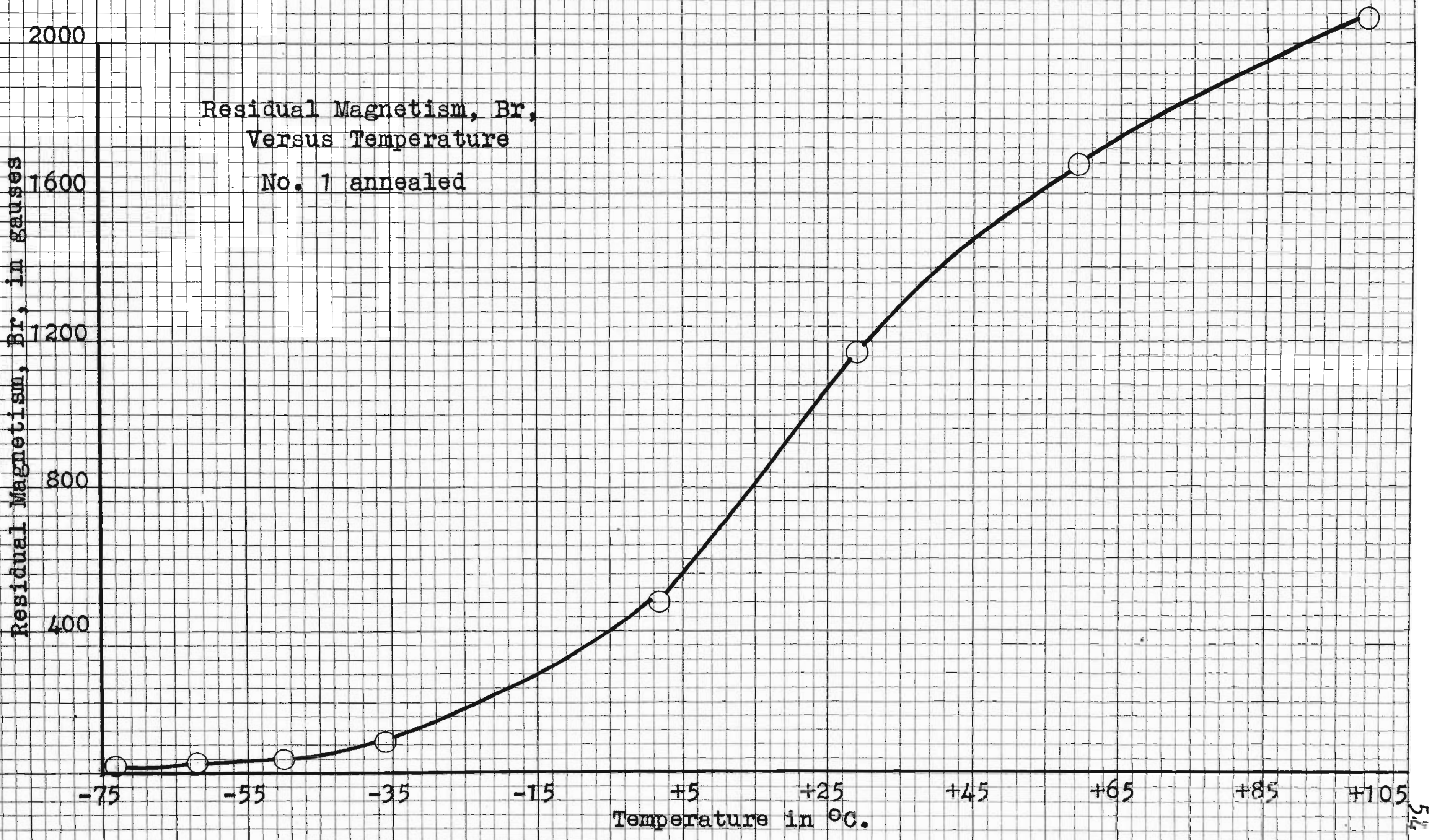

Residual Magnetism, Br,
Versus Temperature
No. 1 annealed
Residual Magnetism, Br, in gauses
2000
1600
1200
800
400
-75
-55
-35
-15
+5
+25
+45
+65
+85
+105
Temperature in °C.

Figure 7-A

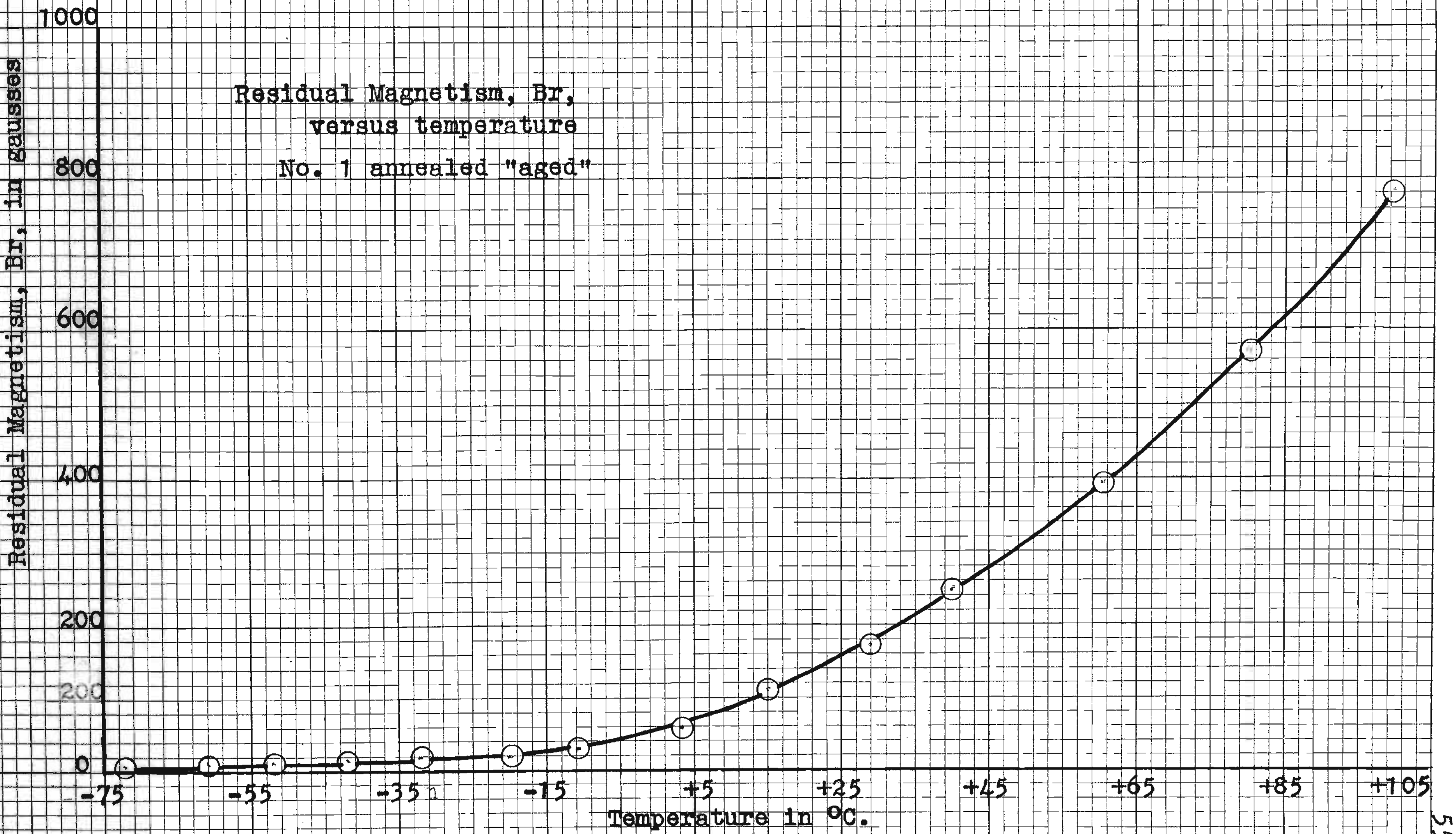
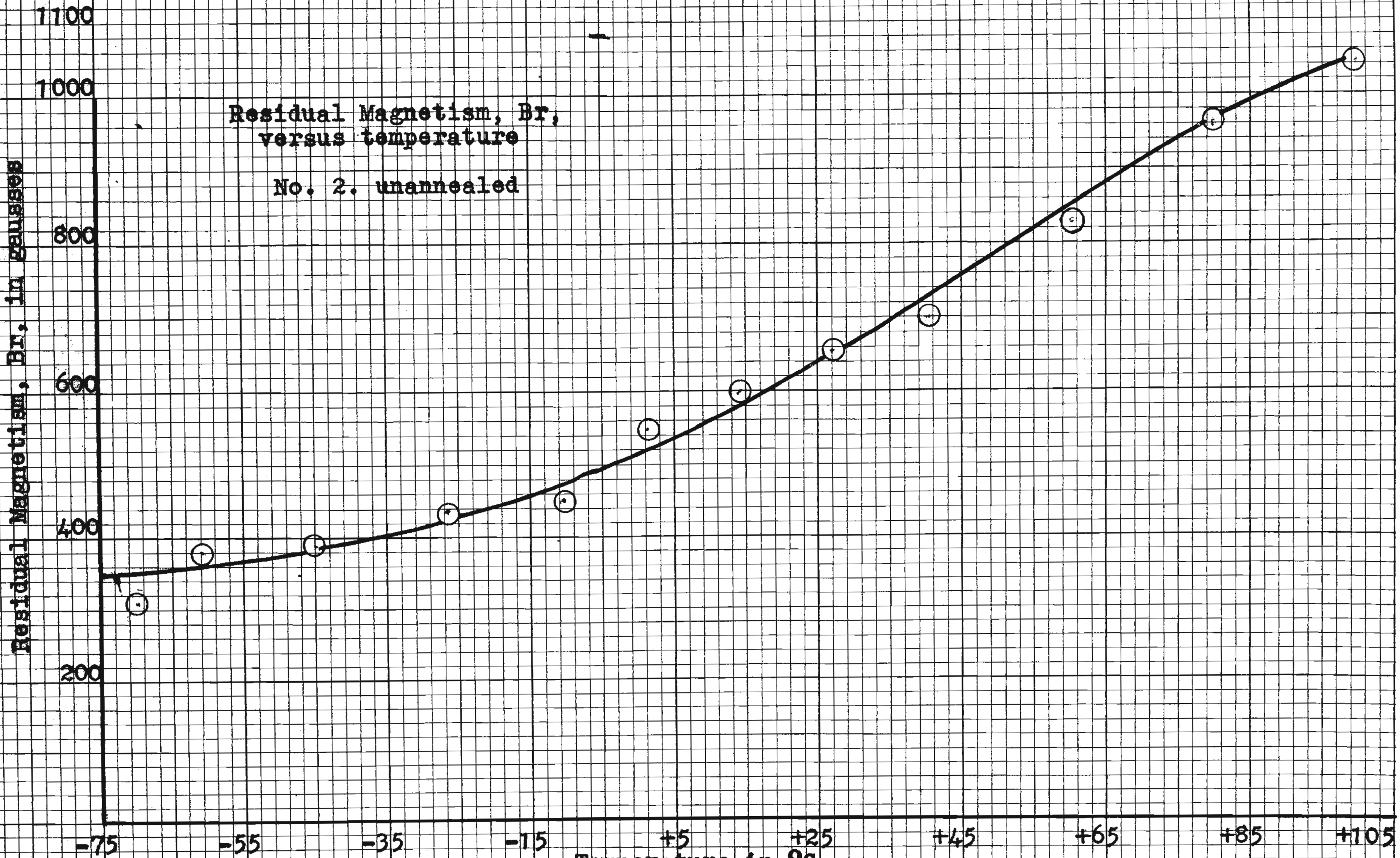

Residual Magnetism, Br,
versus temperature
No. 1 annealed "aged"
Residual Magnetism, Br, in gausses
1000
800
600
400
200
200
0
-75
-55
-35
-15
+5
+25
+45
+65
+85
+105
Temperature in °C.

Figure 7 - B.



Residual Magnetism, Br,
versus temperature

No. 2. unannealed

Figure 7 - C

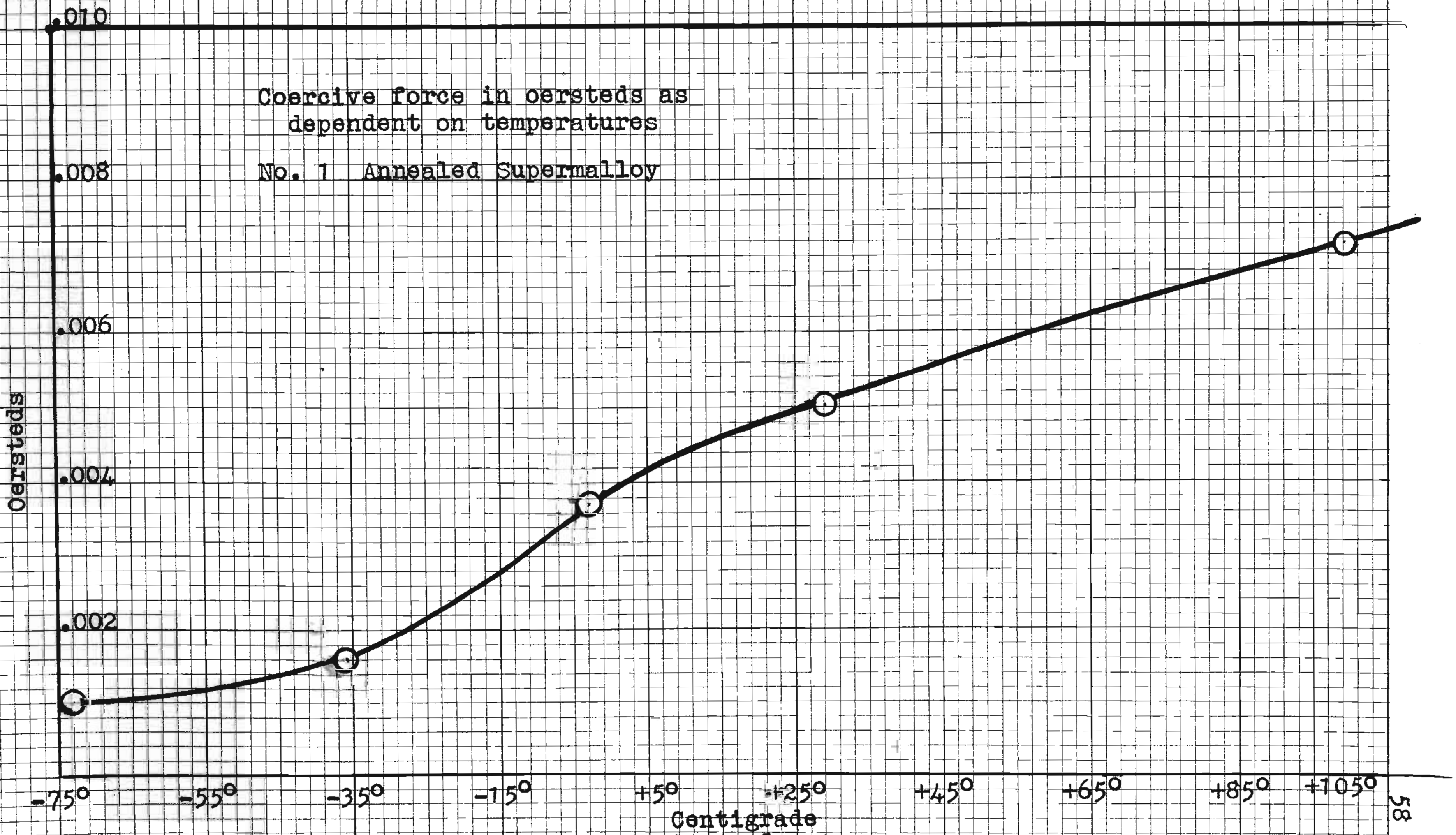
TABLE 9

Coercive force in oersteds as dependent on temperature

	$-73^{\circ}C.$	-36°	$+2^{\circ}C$	$+29^{\circ}C$	$+99^{\circ}C$
Sample No.1 Annealed Supermalloy	0.001	0.0016	0.0037	0.0050	0.0071

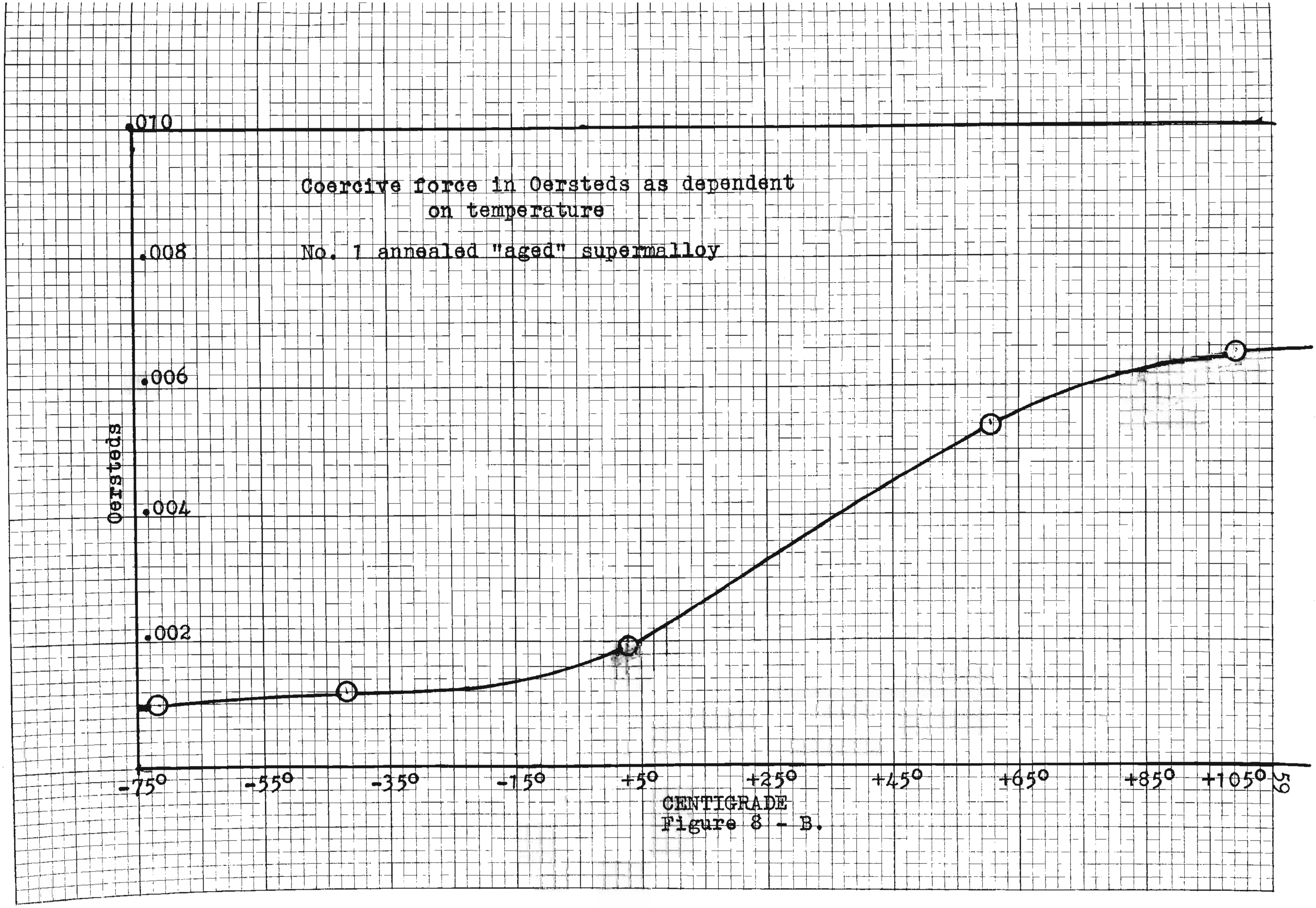
	$-72^{\circ}C.$	$-42^{\circ}C.$	$+3^{\circ}C$	+ 60	$+99^{\circ}C$
Annealed "aged" Supermalloy	.001	0.0012	0.0019	.0054	0.0065

	$-70^{\circ}C.$	$-45^{\circ}C.$	$+1^{\circ}C$	$+40^{\circ}C$	$+99^{\circ}C$
Unannealed Supermalloy	1.78	1.96	2.13	2.26	2.48


Coercive force in oersteds as dependent on temperatures

No. 1 Annealed Supermalloy

Figure 8 - A



Coercive force in Oersteds as dependent on temperature

No. 1 annealed "aged" supermalloy

Figure 8 - B.

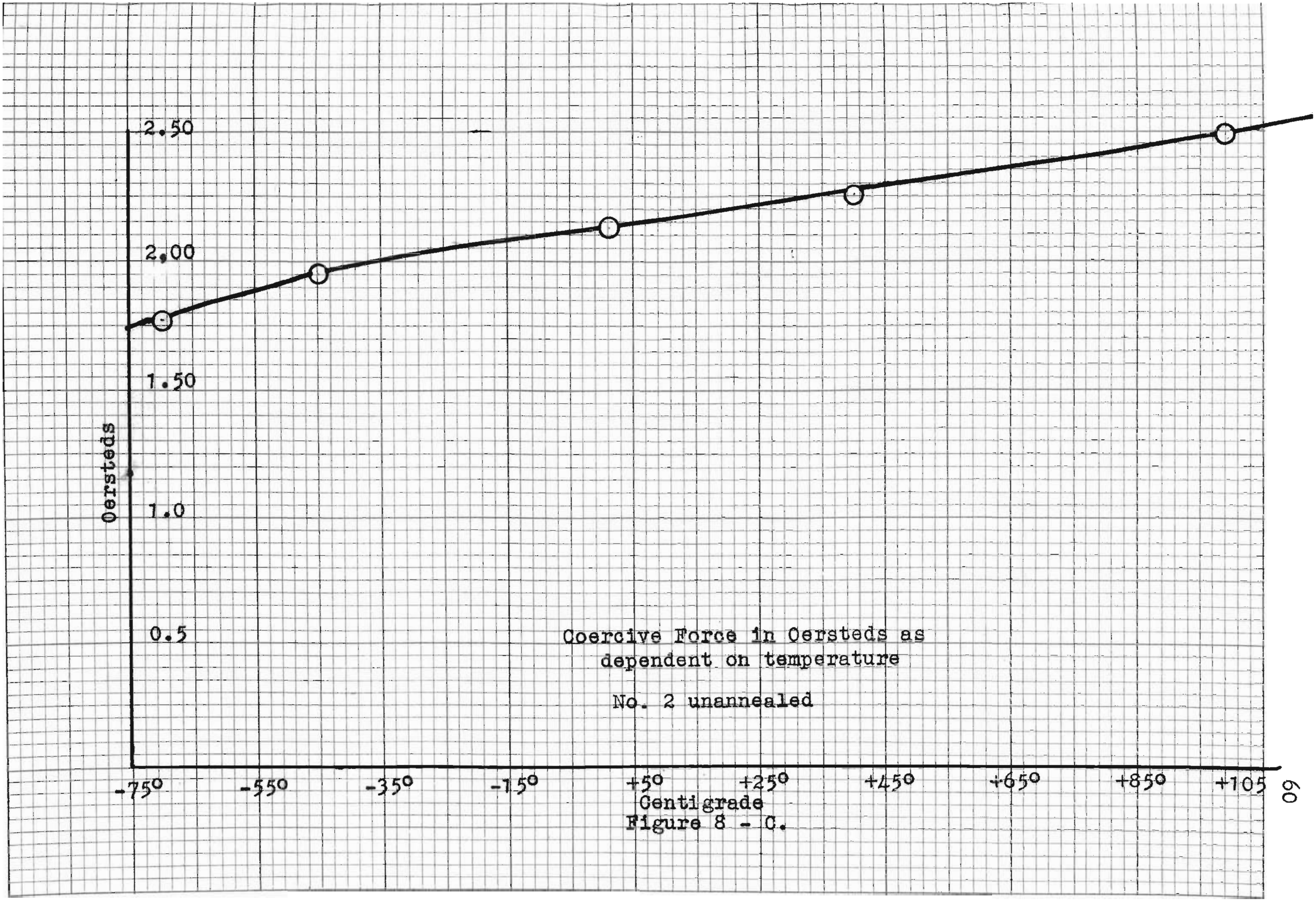

2.50
2.00
1.50
1.0
0.5
Oersteds
-75°
-55°
-35°
-15°
+5°
+25°
+45°
+65°
+85°
+105
Centigrade
Coercive Force in Oersteds as dependent on temperature
No. 2 unannealed

Figure 8 - C.

TABLE NO. 10

$\frac{1}{4\pi}$ times the area of the hysteresis loops in $\frac{\text{ergs}}{\text{cm}^3\text{-cycle}}$ as dependent on temperature.

	-73°C.	-36°C.	+ 2°C.	+ 29°C.	+ 99°C
Sample No. 1 Annealed Supermalloy	0.034	0.050	1.12	2.07	4.42

	-72°C.	-42°C.	+ 3°C.	+ 60°C.	+ 99°C.
Annealed "aged" Supermalloy	0.0064	0.027	0.12	1.03	1.75

	-70°C.	-45°C.	+ 1°C.	+ 60°C.	+ 99°C.
Unannealed Supermalloy	2.50	3.23	4.44	5.59	8.40

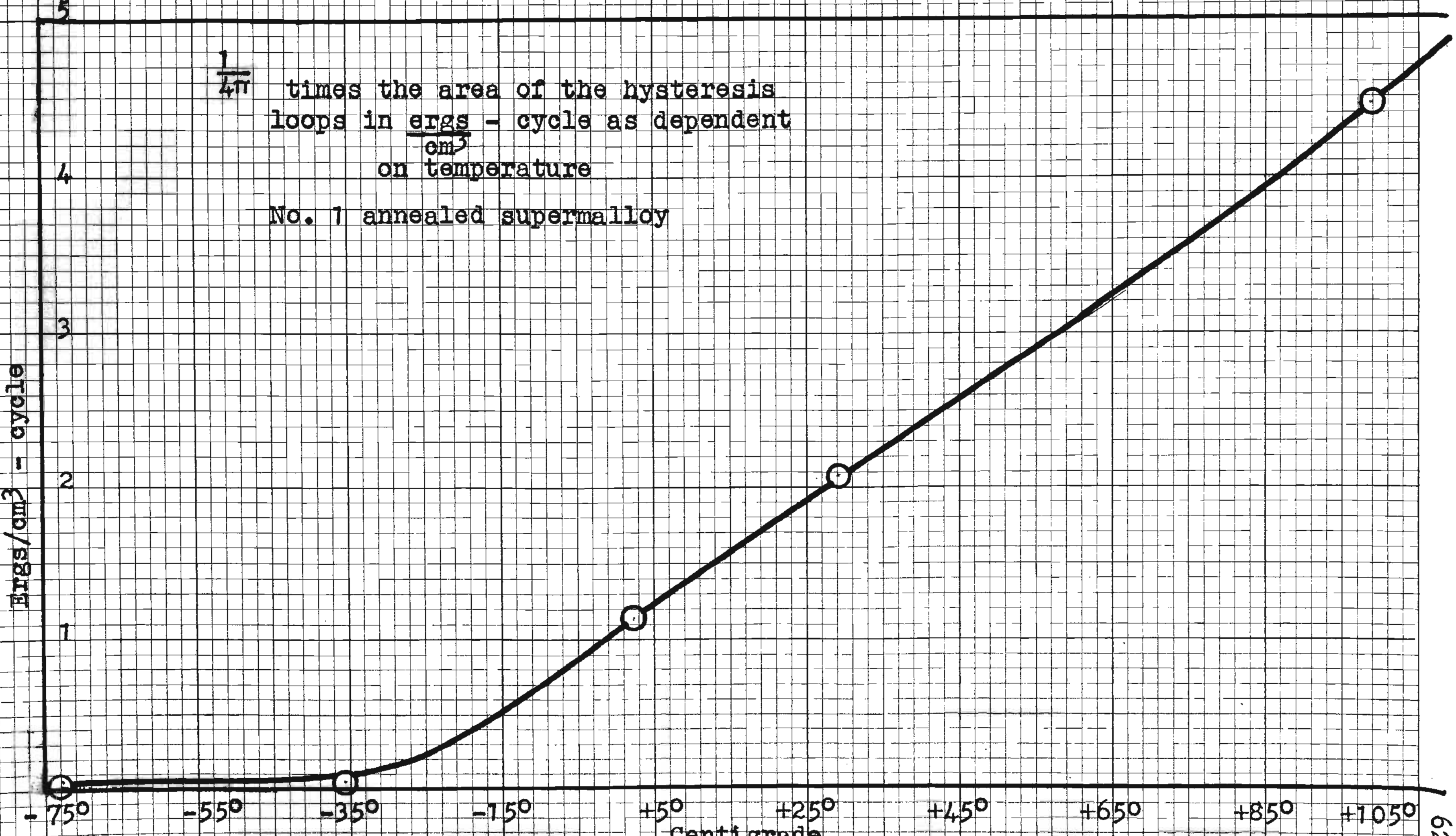

5
4
3
2
1
$\frac{1}{4\pi}$ times the area of the hysteresis loops in $\frac{\text{ergs}}{\text{cm}^3}$ - cycle as dependent on temperature
No. 1 annealed supermalloy
Ergs/cm^3 - cycle
- 75°
-55°
-35°
-15°
+5°
+25°
+45°
+65°
+85°
+105°
Centigrade

Figure 9 - A.

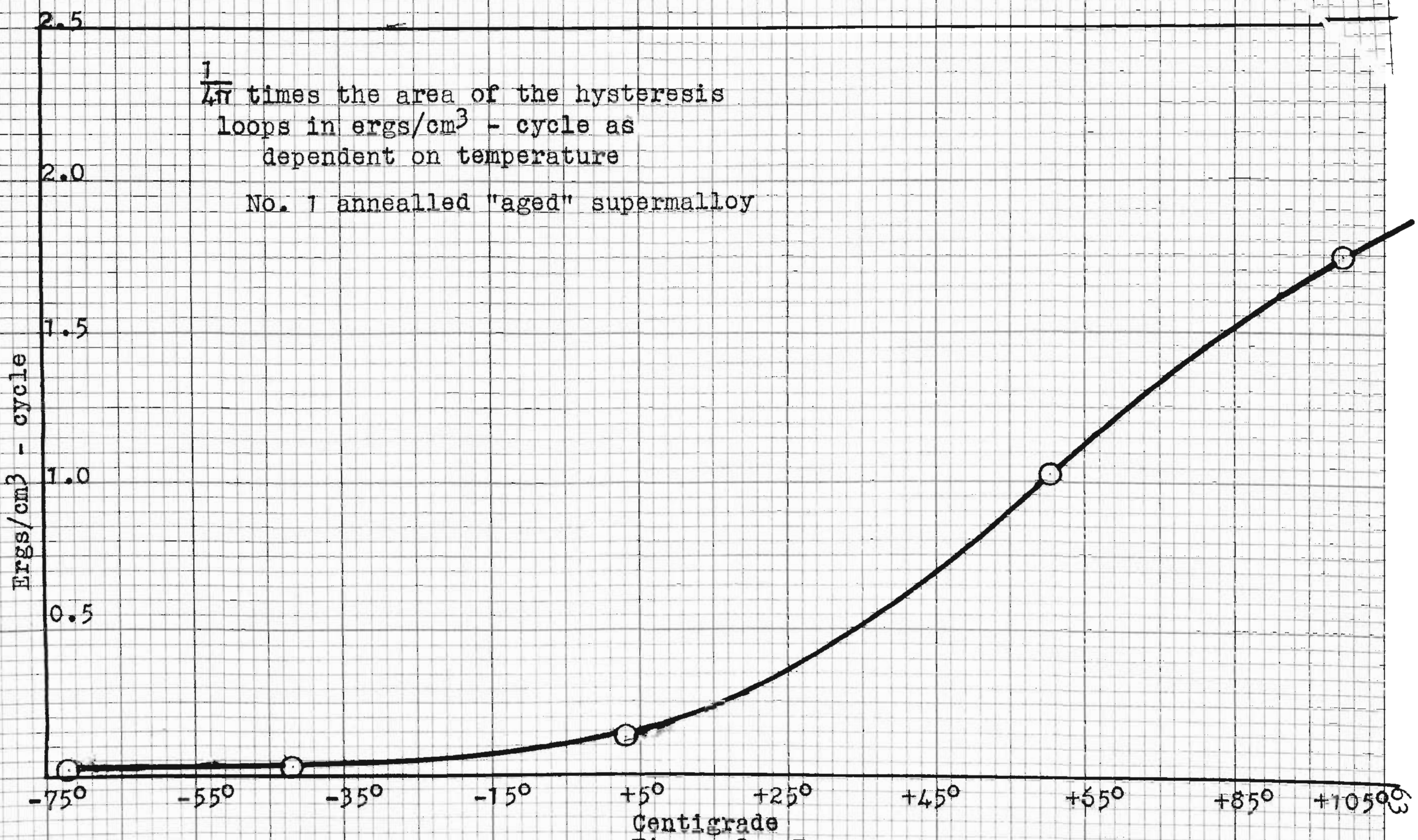

$\frac{1}{4\pi}$ times the area of the hysteresis loops in ergs/cm^3 - cycle as dependent on temperature
No. 1 annealled "aged" supermalloy
2.5
2.0
1.5
1.0
0.5
Ergs/cm3 - cycle
-75°
-55°
-35°
-15°
+5°
+25°
+45°
+65°
+85°
+105°
Centigrade

Figure 9 - B

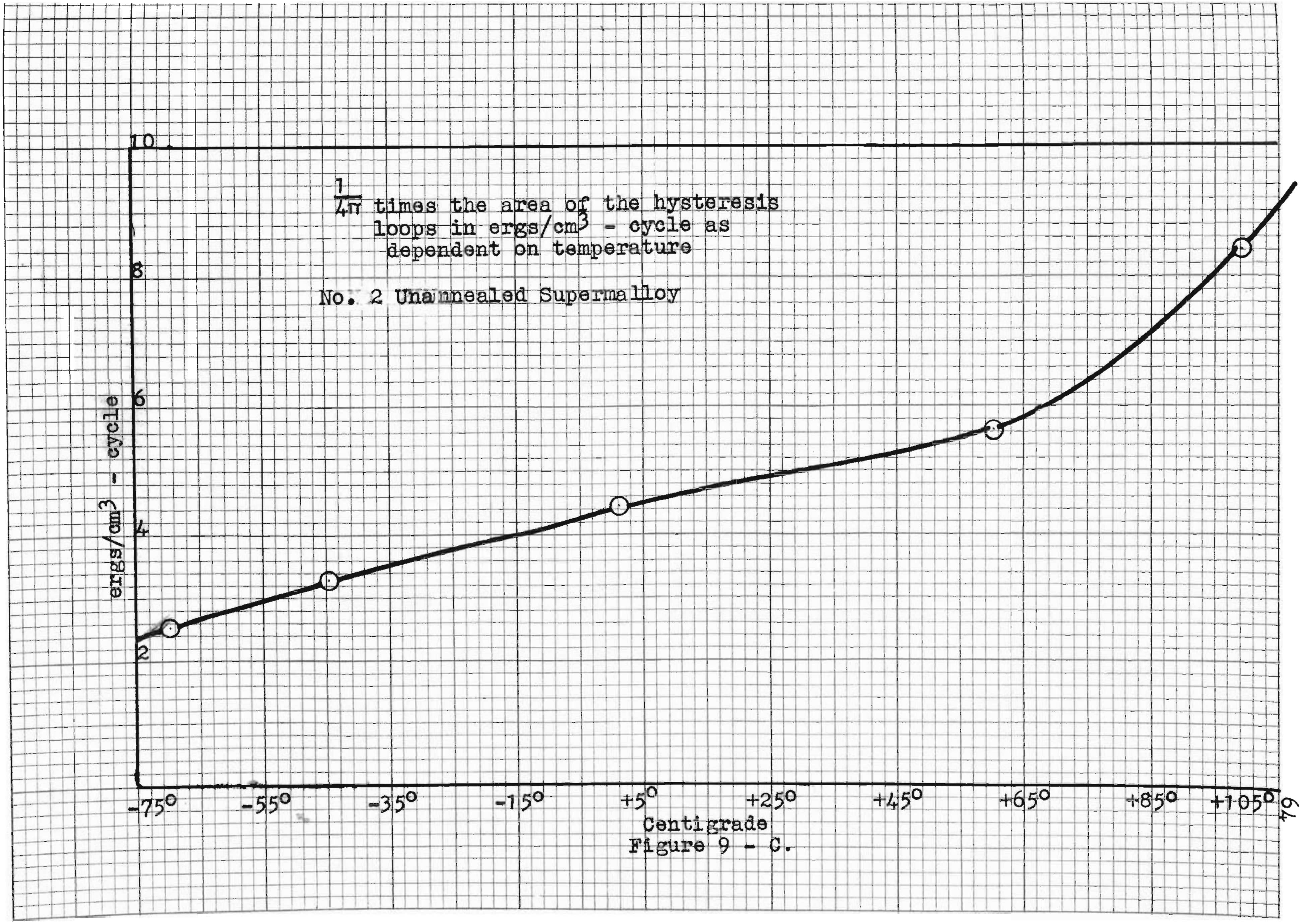

$\frac{1}{4\pi}$ times the area of the hysteresis loops in ergs/cm^3 - cycle as dependent on temperature
No. 2 Unannealed Supermalloy
10
8
6
4
2
ergs/cm^3 - cycle
-75°
-55°
-35°
-15°
+5°
+25°
+45°
+65°
+85°
+105°
Centigrade

Figure 9 - C.

CONCLUSIONS

There is definitely an increase in hysteresis loss as the temperature is raised as shown by the tables and graphs of the hysteresis loops. There is also an increase in permeability μ, in residual magnetism, and also in coercive force as the temperature is raised for supermalloy for the temperature ranges of -73°C. to 100°C.

Sample No. 1 annealed supermalloy had the highest permeability, μ, sample No. 1 annealed "aged" had the next highest permeability and the unannealed specimen had the lowest permeability μ. Of the two annealed specimens, the "aged" one had the lowest residual magnetism, Br, for the same field intensity and temperatures.

No other work has been done with which these results could be compared except at room temperature by Bozarth,(20) and his associates. They obtained a hysteresis loss of approximately one $\frac{\text{ergs}}{\text{cm}^3\text{-cycle}}$ for a maximum induction of 1900 gausses. The author ran two tests on Supermalloy at room temperature and obtained an average loss of 2.07 $\frac{\text{ergs}}{\text{cm}^3 - \text{cycle}}$. It is assumed that the test made by R. M. Bozorth was made at room temperature.

The other work that was done comparable to this was done by Earle M. Terry(21) in 1910 on electrolytic iron.

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(20) Bozorth, op. cit., pp. 29-86.

(21) Terry, E.M. The effect of temperature upon the magnetic properties of electrolytic iron. Physical Review, Vol. 30, pp. 133-160, 1910.

He found for the annealed specimens that the permeability, μ , and residual magnetism for low fields increased with rise of temperature with the range of -73°C. and $+ 100^\circ$C. But for the coercive force and hysteresis loss, he found a decrease. For the unannealed specimens, he found an increase in permeability, but a decrease in hysteresis loss, retentivity and coercive force with a rise in temperature. The author found an increase in all three, permeability, residual magnetism and coercive force for Supermalloy at these temperature ranges.

It appears that there are two main considerations to take into account in order for Supermalloy to have such a high permeability, μ , and they are:

(1) Purity: Impurities such as silicon, carbon, sulfur, etc., are lower than in most commercial alloys. The presence of certain impurities or combinations of impurities, usually found in commercial alloys, will prevent the attainment of high permeability.

(2) Heat treatment: A definite cooling rate must be used below the temperature at which atomic ordering begins. It will lose this high permeability, μ, with rough temperature treatments. Sample No. 1 annealed was subjected to temperature changes from -73°C. to 100°C. in rapid succession for about five times. After this treatment, it had only about 40 per cent of the permeability as it had before this treatment.

No other work has been done with which these results could be compared but an analysis of the results for the two annealed specimens indicates their probable accuracy. For example at -73°C., the "aged" sample had about 40 per cent of the permeability as the one before rough treatment and at 100°C. it still had about 40 per cent the permeability of the other.

ERRORS

Of the various methods that have been used for magnetic testing, the Rowland ring seemed best suited for the present work. Since it gives a continuous magnetic circuit without a joint of any kind, no correcting for demagnetization effect is necessary, and with a fairly uniform winding of the magnetizing coil, it may be safely assumed that the flux crossing each section of the ring is the same, and that the leakage is negligible. It is, however, subject to three sources of error:

(1) The field is not uniform across the specimen, and further, the mean field is not the field at the center of the section calculated from the ampere turns.

(2) Since permeability is a function of field strength, the mean flux density, calculated from the deflections of the galvanometer, is not the flux density at the center of the section.

(3) If Supermalloy is like iron as pointed out by Ewing and Rayleigh for small fields and fields for which the differential $\frac{dB}{dH}$ is large changes its magnetic state slowly,sometimes requiring several seconds, will introduce a serious error. Since the ballistic method requires that the total change shall take place before the galvanometer swings appreciably from its zero position, a serious error is introduced in testing materials possessing "magnetic inertia".

The first two errors was reduced to negligible magnitudes by choosing the width of the ring small in comparison to its diameter.

There is bound to be error in this experiment due to the precision measure of the instruments. The precision measure of the microammeter used to measure the magnetizing current for the annealed samples was fifty microamperes, which was better than one per cent of the value of current used. The ammeter used for the unannealed specimen had an error of about 0.33 per cent due to the precision measure. Both these instruments had an approved accuracy of $\frac{1}{2}$ to 1 per cent. The precision measure of the galvanometer was 0.5 mm. All the resistances were accurate within 1 per cent. Errors were minimized by averaging a large series of readings.

SUMMARY

Warburg was the first to show that the energy loss due to hysteresis was equal to $\frac{1}{4\pi}$ times the area of the hysteresis loop when H was in oersteds and B in gauss. Steinmetz developed the relationship

$$W_h = \eta B^k_{max}$$

where k was given the value of 1.6. Then Kennelly advanced what is now called Kennelly law in the form of

$$\rho = \alpha + \sigma H$$

Then Rayleigh found that the law

$$B = \mu_o H + aH^2$$

was still a better law.

Earle M. Terry found in 1910 that temperature does have a marked influence upon the magnetic properties of iron.

R. M. Bozorth and his associates at the Bell Telephone Laboratories have done a lot in developing alloys with high permeability at low fields with small hysteresis losses.

Magnetization curves and hysteresis loops are explained today by means of the Domain Theory of Magnetism.

Temperature definitely does have a marked influence upon the magnetic properties of Supermalloy. Annealed Supermalloy was found to have a permeability of 196,000 at H = 0.0097 oersteds at 99°C. and a hysteresis loss of about 2 $\frac{\text{ergs}}{\text{cm}^3\text{-cycle}}$ at room temperature.

There is definitely an increase in permeability, , residual magnetism Br, and coercive force for a rise in temperature for a range of -73°C. to 100°C. in low field intensity for Supermalloy.

The study of this problem is by no means exhausted; I would like very much to continue the study of the effects at different field intensities and different temperature ranges. Also I would like to measure the effect on Supermalloy when a pressure is applied during magnetization, both longitudinal and transverse.

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