REDUCTION OF MAGNETOSTRICTION IN SILICON-IRON SHEETS

A Dissertation Submitted to the Faculty of the
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DOCTOR OF SCIENCE

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1.0 - DEVELOPMENT OF THE PROBLEM

Magnetostriction became important to the manufacturer of electrical steel sheet materials through his constant endeavor to produce a material of "magnetic quality" superior to that of his competitor. It is of interest to examine the factors that are specified as "magnetic quality".

Permeability and core loss are two criteria which determine the design constants of a power or distribution transformer. These characteristics are important in the determination of the size of the core for a given application. It is recognized that for a given rating or a given application the transformer with the smallest physical dimensions will be the one favored by the user. Small size means small cores; small cores mean less iron and less copper per unit, which, for a given rating, means lower cost to the manufacturer and user. As the size of the core is diminished, a point is reached at which one of two phenomena occurs. First, the exciting current may become exceedingly large because of the values of the field H necessary to energize the transformer to the induction B, at which the unit must operate. This exciting current represents not only a large power loss but is reflected in the flux wave and causes distortion of the output voltage wave shape. The value of induction, B, in a core for a given applied field, H, is determined by permeability $\mu=B/H$, which is a property of the core material. When exciting currents are the limiting design characteristic, the electric steel producer whose product possesses the highest permeability is in the favored position. The processing variables that most influence the permeability have been found to be (1) purity of the iron, (2) freedom from stress and strain, and (3) orientation of the crystals in the material. By proper control of these variables, materials with superior permeabilities for transformer cores have been produced during the last 45 years.

With high permeability attained, there is still a limitation on the smallness of the core which is imposed by another characteristic of the material, the "core loss". Core loss is present in a transformer that is energized. As the core in a distribution transformer is energized at all times, whether or not power is used, this is a large expense item. Hence, it must be minimized. Minimization of core loss can be accomplished only through reduction of its components; namely, eddy current and hysteresis.

Eddy current losses are reduced by two methods:

(1) Decrease the cross-sectional area through which the eddy current may flow by decreasing the thickness of the material (sheet).

(2) Add an alloying element to increase the electrical resistivity of the material, i.e., silicon. The alloying element must be chosen so as not to harm the permeability or hysteresis by other than a dilution effect.

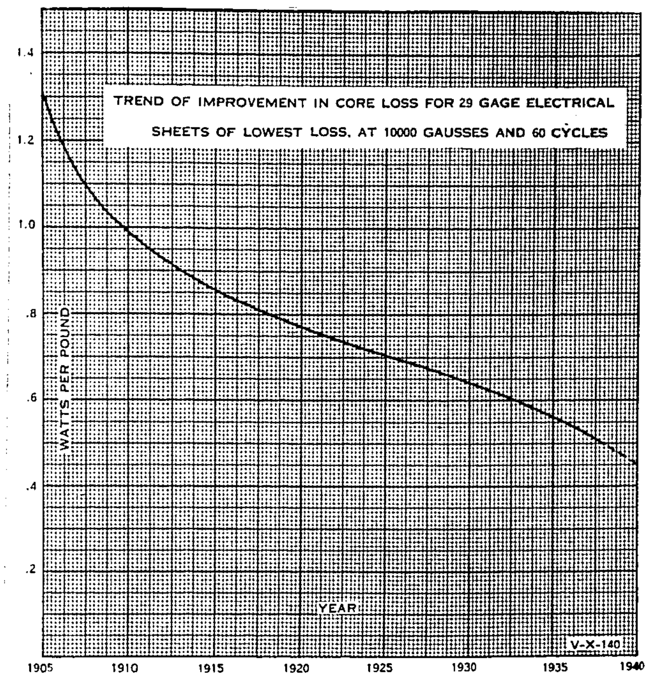


Fig. 1

The first of these items, i.e., reduction of area, is limited by the rolling equipment available and the cost of making the reduction. With ordinary commercial equipment the thickness (gage) of the material will be .013 inches to .015. By the use of special equipment, it is possible to reduce this figure to .0025-.0020 inches. The addition of silicon as an alloying element is very successful until a value of about 6.00% is reached. At approximately this value the material becomes so brittle that it cannot be worked without breaking into small pieces.

Hysteresis loss is related to the purity of the material, that is, with respect to iron and silicon. In general, one can say that the more pure the material, the less the hysteresis loss. Grain size is also a factor in reducing this loss, the larger the grain the lower the loss.

There are other important properties of commercial transformer core materials. One of these is flatness; if a sheet is not flat, strain will be introduced when the transformer laminations are stacked into a core and thus spoil the magnetic quality. Another property is the interlamination resistivity which is necessary to make the thin cross section of the material effective in reducing eddy current loss. This is accomplished by producing a thin, high resistance film on the steel such as a silicate or oxide. The two factors that have just been mentioned are related to a third which is known as the "space factor". This is the fraction of the space available in the core that may be utilized by iron laminations. Commercial materials have a space factor as high as .95.

In the foregoing discussion, emphasis has been placed on the trend that caused transformers (and hence their cores) to become smaller and smaller as steels of high magnetic quality became available. For a given rating the number of lines of magnetic flux in the core tend to be a constant in a given design. As the dimensions of the core decrease, the flux density (lines/area) will become larger and larger. In 1910, a flux density (B) of 10 to 12 kilogauss was considered high for power transformers; in 1935, it was 12.0 to 14.0; and by 1945, values of 16.0 to 18.0 were being used.

As the induction was increased, transformers of two types began to cause complaints and claims to be received by the manufacturer because of "noise". The first of these consisted of units that are placed in vaults under sidewalks to distribute power to apartment houses in populous areas. The other application was in the transformers on the big transmission lines where the size of the unit was limited by the loads that can be carried by the railroad and pass through railroad tunnels. In both of these applications the designs call for as high an induction as possible, for size is the controlling factor.

2.0 - ANALYSIS OF TRANSFORMER NOISE

As it was possible that noise could become a controlling factor in transformer design, the manufacturer initiated steps to place definite controls on this characteristic. In the transformer market, "noise" became a very definite sales argument, and soon caused noise specifications to appear in contracts. Noise analysis of transformers resulted in the establishment of the following facts:

(a) The "noise" consists of a 120-cycle fundamental.

(b) Harmonics even and odd were present up to and including at least the ninth.

(c) In a given design of transformer, it was found that wide variations of noise level could be expected from "identical" units. Transformers built as nearly alike as possible would produce noise levels as much as 10 decibel apart. This allows the conclusion that the variables are not being controlled.

(d) The source of the noise was the core which was vibrating at these frequencies. The core pulsated as a unit at the fundamental 120-cycle frequency. The dimensions of the core fluctuated with the applied voltage wave, differences from standard being greatest when the applied voltage wave was at a maximum or minimum.

The phenomenon of the change in length in a material when magnetized is known to the physicist as the Joule magnetostriction effect. It is usual in this phenomenon to measure the change in length ($\frac{\Delta L}{L}$) parallel to the direction of magnetization.

3.0 - STATEMENT OF THE PROBLEM

Elimination or reduction of magnetostriction in core material should solve the noise problem in transformers. This is the most effective method, for the control of the noise source is an answer to the "noise problem". As the control of the phenomenon is important in electrical steel for transformer cores, it is necessary to review at this point the characteristics of this special purpose sheet steel.

Chemical Analysis

Element	Range in Per Cent
Silicon	4.75-5.00
Carbon	0.06 max.
Manganese	0.08 max.
Phosphorus	0.030 max.
Sulfur	0.028 max.

Inspection of the table shows that the material is essentially a high purity iron with silicon added to increase the specific resistivity. The steel is sold to the transformer fabricator in the form of a sheet of thickness .013 to .015 inch. The length and width are specified so as to produce the cores with the smallest possible wastage of material. Usual widths run from 20 to 48 inches, with length being any that is desired. These sheets are fully annealed at high temperatures and then delivered to the customer. This anneal has for its purpose relief of stress in the material, production of the desired flatness, growth of large grains (1 to 10 grains/mm^2), development of a satisfactory electrically resistant surface, and purification of the magnetic material.

The magnetic quality of this commercially produced material is best presented in the form of a series of graphs. These follow:

The magnetic properties are determined by American Society for Testing Materials methods on samples that are cut from the sheets. They measure 3 cm. x 50 cm. x gage of sheet. These are known as standard Epstein strips. Enough of these thin strips are stacked together to give the desired sample weight.

4.0 - LITERATURE REVIEW

Many workers have contributed to the magnetostriction field, but from the mass of data, very little is directly applicable to the problem at hand. This is the direct result of two factors, namely:

(1) Use of samples of unknown histories, i.e., physical, chemical, and magnetic properties.

(2) Use of the applied field, H, as the independent variable.

The best description of the magnetic state of a material is given by the induction, B, which is related to H through the permeability μ, where $\mu = B/H$. The value of μ

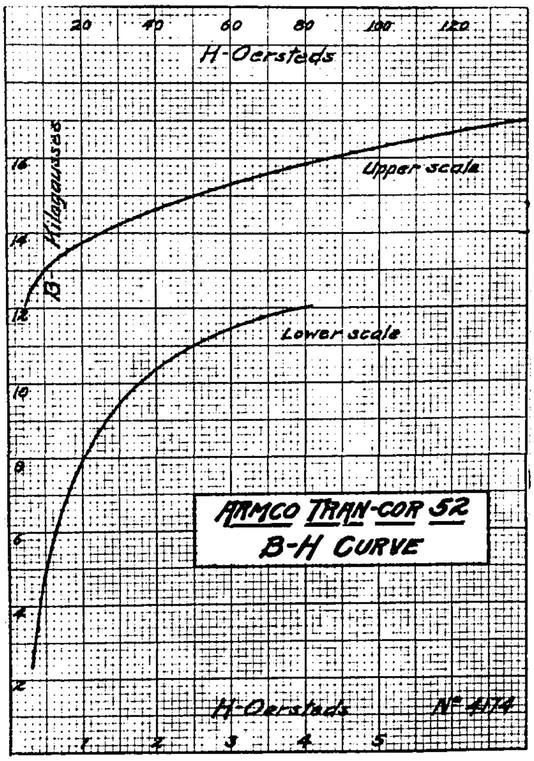


Fig. 2

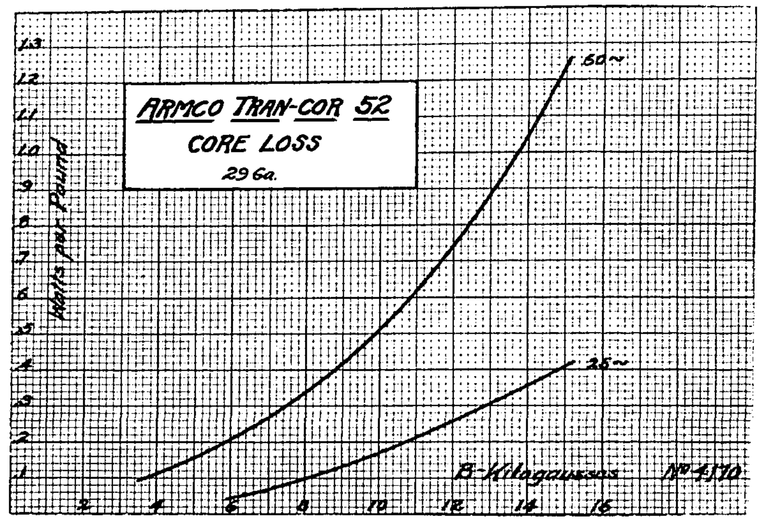


Fig. 3

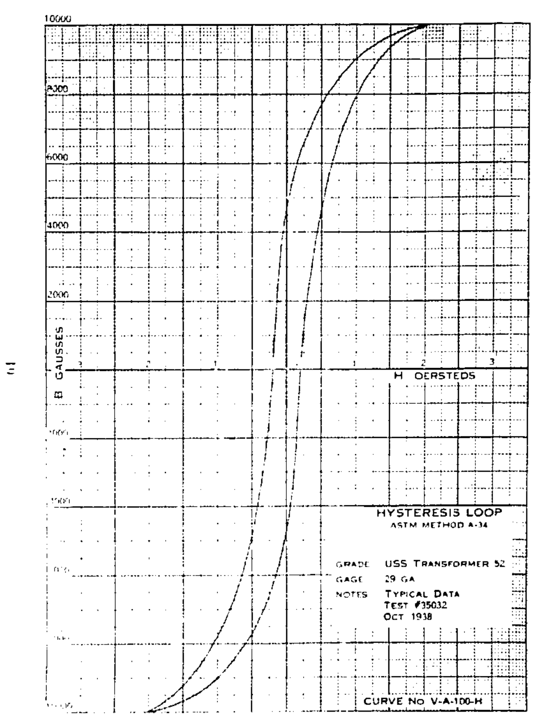


Fig. 5

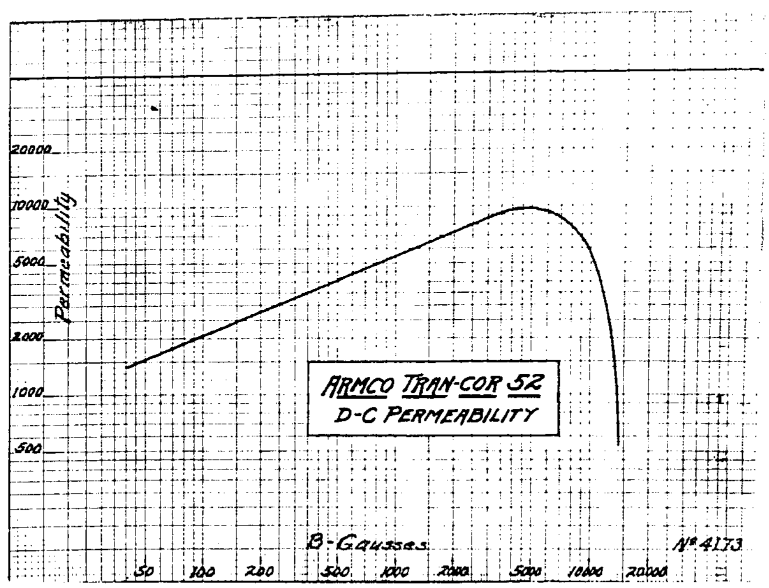


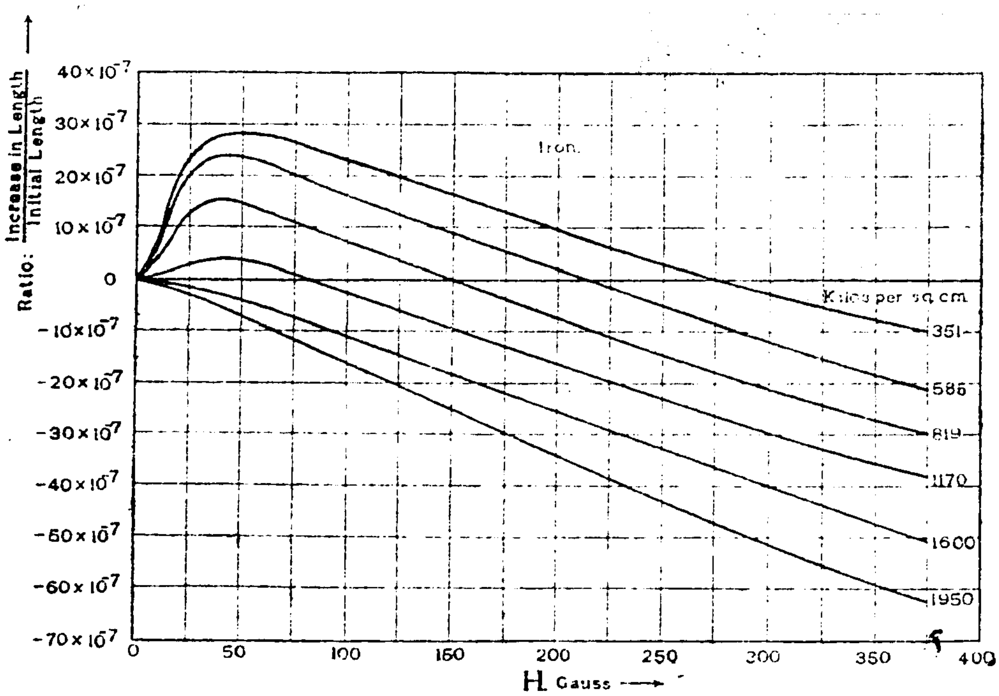
Fig. 4

is very sensitive to previous history, which means that without a specific statement of the nature of the function μ, the induction cannot be determined. Without this, a comparison of materials for transformers cannot be made, as the design is based upon the economically attainable value of induction. In spite of these inadequacies, some of the characteristics of the phenomena of magnetostriction that will be met in the experimental investigation are worth discussion. The work of Bidwell is representative of the work on polycrystalline materials. The results of his investigation are presented in Fig. 6. The important features of magnetostriction to be noted are:

a. Iron shows both positive and negative magnetostriction. A sample may lengthen or shorten in the direction of the applied field.

b. Tension applied on the sample will cause a reduction in the observed magnetostriction.

The work of Webster is representative of the measurements made on single crystals of iron. This work has been repeated by Honda and Masiyami, and the results obtained were in substantial agreement with Webster.



Bidwell's Curves of Magnetostriction vs. Applied Fields for Various Values of Tensional Stress.

Fig. 6

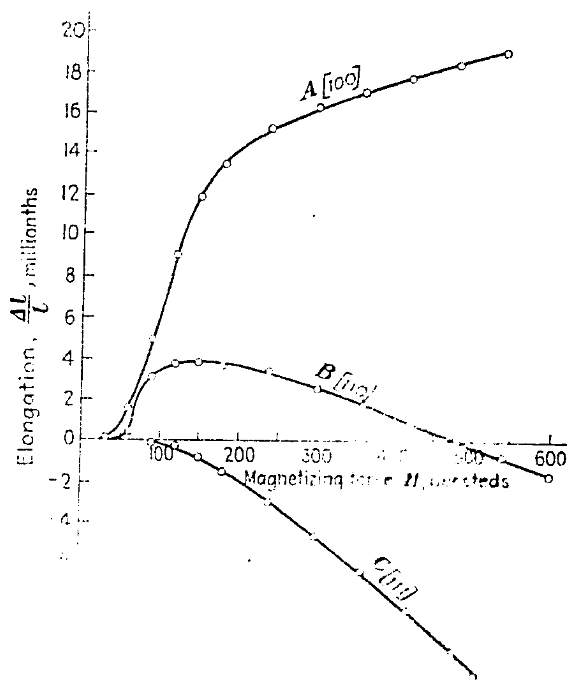
Fig. 7 represents these data. With samples of this type we observe three types of curves:

a. Magnetization along the [100] crystallographic axis produces a positive magnetostriction.

b. Magnetization parallel to [111] axis produces only negative magnetostriction.

c. Magnetization along [110] axis produces first a positive effect, followed by a negative effect similar to a polycrystalline sample.

It is convenient to discuss the literature on the basis of the material tested. The classifications are (a) single crystals, and (b) polycrystalline materials.



...riction of an iron single crystal (Webster.(640))

Fig. 7

(a) Single Crystals

The work of Heaps[1] on a circular disc sample cut from a single crystal of silicon iron sheet donated by General Electric Company gave rise to the curves in Figs. 8, 9, and 10. The orientation of the crystallographic axes in the sample was unknown. A Weise electromagnet was used to produce the magnetizing fields which are at such high values that the region in the vicinity of the origin is compressed so that their nature in this region is doubtful. Heaps also found that rotation of the disc slightly to the right or left out of the parallel position to the magnetic field caused great variation on the observed value of the elongation. These are shown by the dotted lines in the figures.

Webster[2] in his work on single crystals had samples of known history. The direction of the crystallographic axes was accurately determined by X-ray methods. The samples were in the form of rods approximately 6 cm. length by 0.5 cm. diameter. The testing equipment was so constructed that both the magnetizing force (H) and the intensity of magnetization (I) of the sample could be determined. These data are represented graphically

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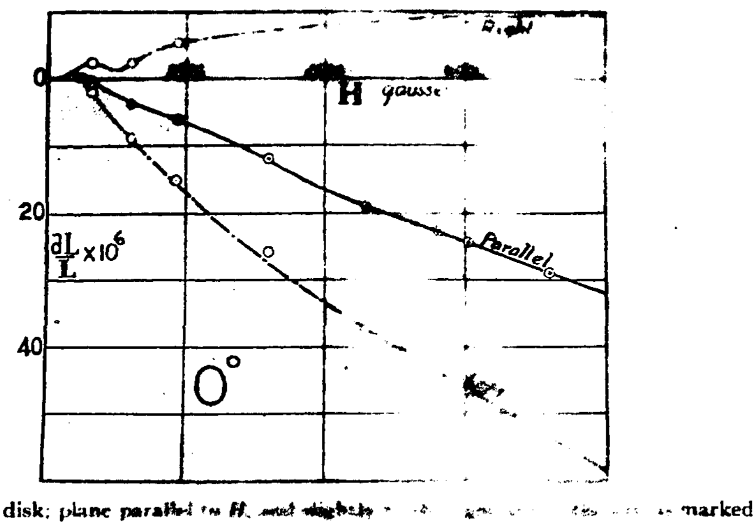
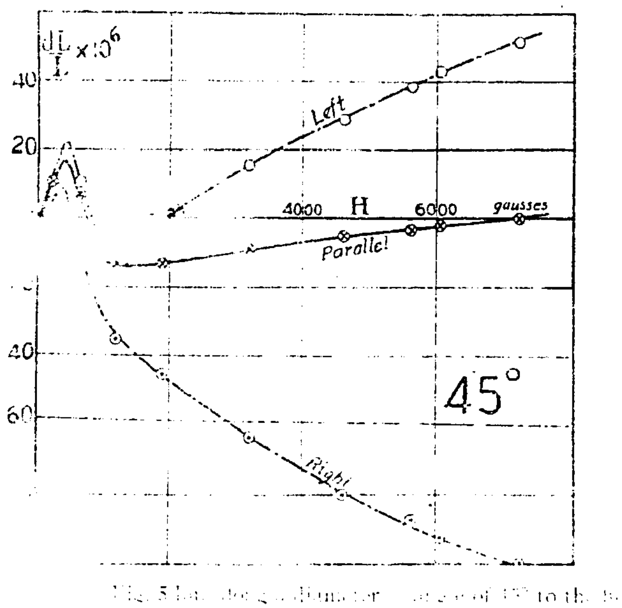
1) Heaps - Phys. Rev. 22 (1923) - 486-501.

2) Webster - Proc. Roy. Soc. Ser. A (1925) 109, 570-584.



Magnetostriction of a Single Crystal of
Silicon-Iron in Form of a Circular Disc (Heaps)

Fig. 8



Magnetostriction of Disc
Rotated 45° from Fig. 8 (Heaps).

Fig. 9

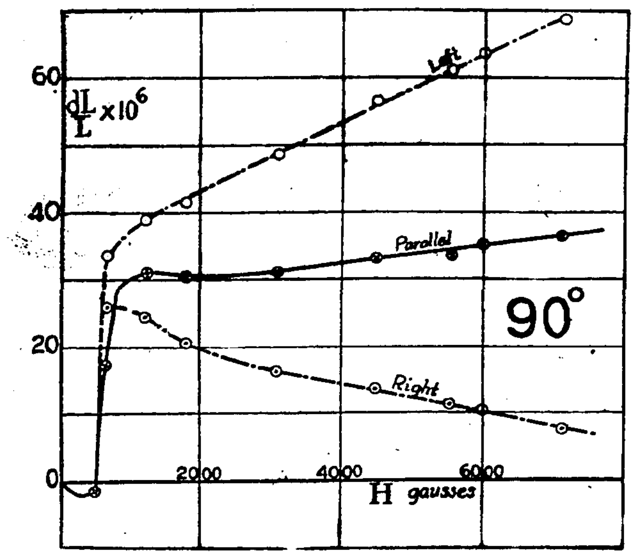


Fig. 7. Same as Fig. 5 but along a diameter perpendicular to the first

Magnetostriction of Disc Rotated 90°
from Fig. 8 (Heaps).

Fig. 10

in Figs. 7, 11, and 12. The work of Honda and Masiyama[3] confirmed and extended these results as illustrated by Figs. 13, 14, 15. Williams[4], in measurements on single crystals prepared by Ruder, of General Electric Company, obtained the curves presented in Figs. 16, 17. It is to be noted that the curves in Fig. 17 are not smooth.

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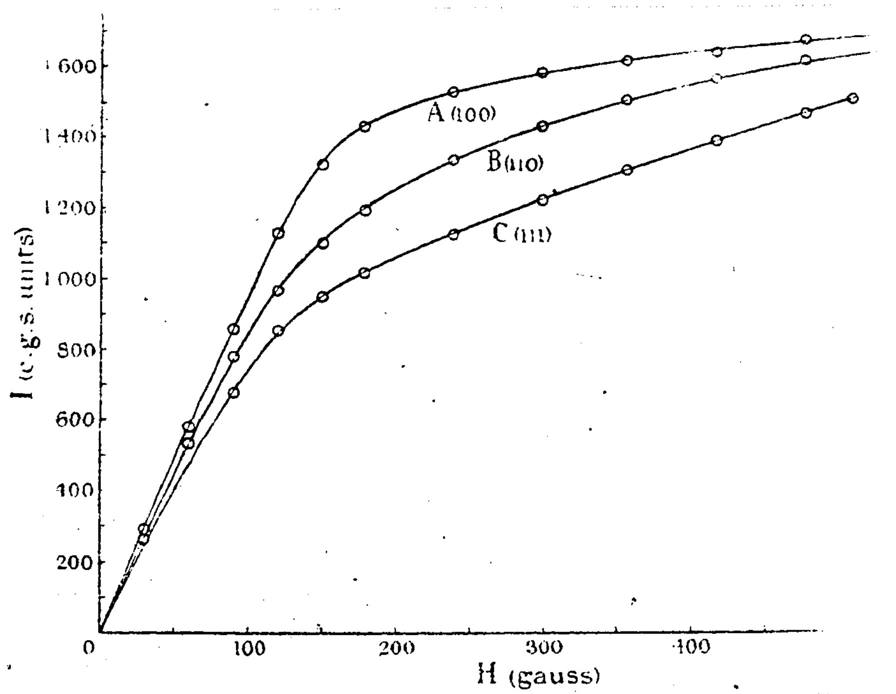
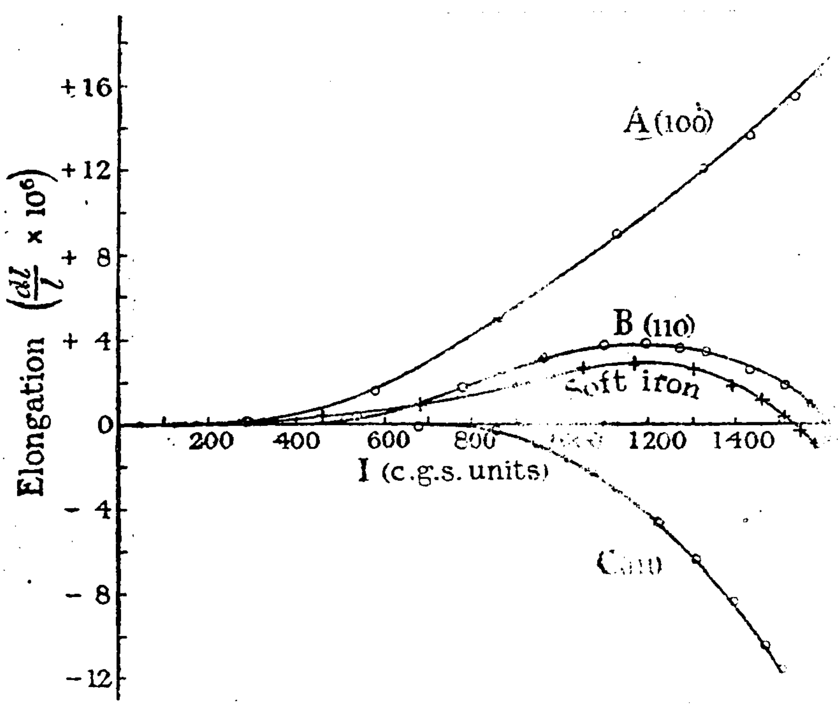
3) Honda and Masiyama - Sc. Rpts. Tohuka Imp. Univ., 15 (1926), 757.

4) Williams, S. R. - Testing 1 (1924), 190-193.



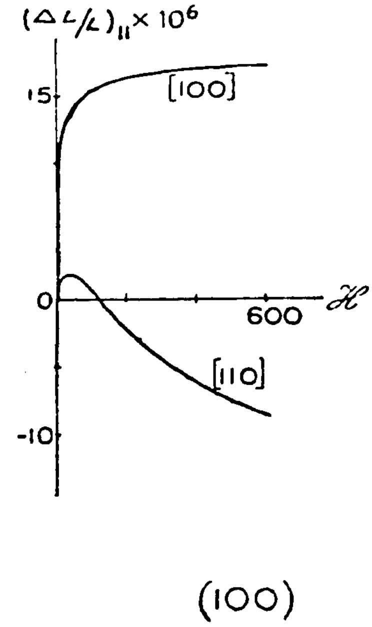
I vs. H for Webster's Crystals.

Fig. 11



Magnetostriction of Webster's Crystals
vs. Intensity of Magnetization.

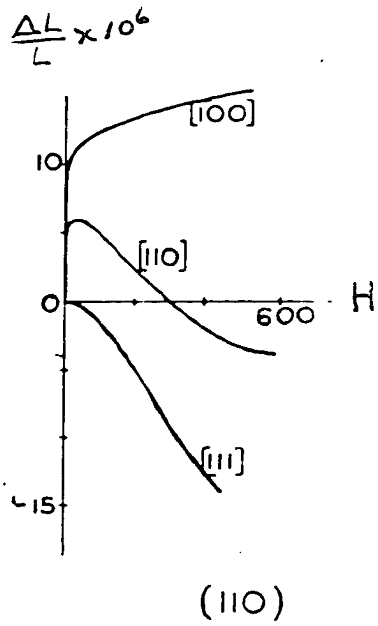
Fig. 12



(100)

Fig. 13

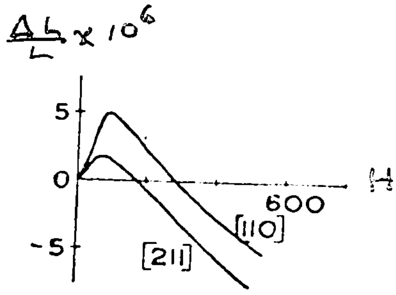
Magnetostriction measured parallel to various crystalline axes when magnetized parallel to the [100] axis.



(110)

Fig. 14

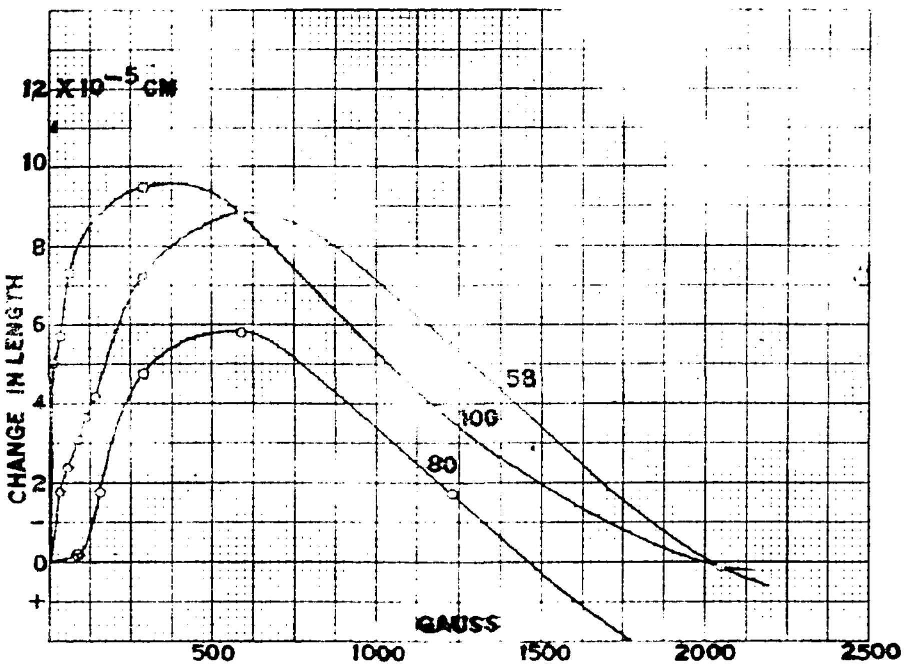
Similar to Fig. 13, except magnetization is parallel to [110] direction.



(111)

Similar to Fig. 13, except magnetization is parallel to [111] direction.

Fig. 15



Magnetostriction of Single Crystals of Iron (S. R. Williams).

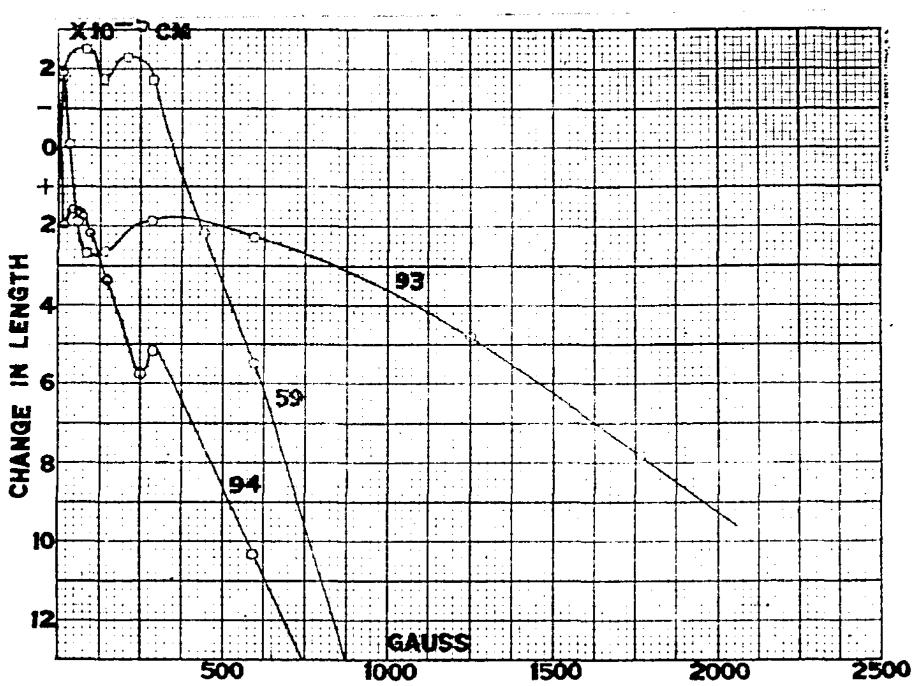
Fig. 16

These data are interpreted as follows:

(1) Magnetization parallel to a [100] axis in iron produces positive magnetostriction.

(2) Magnetization parallel to a [111] axis produces negative magnetostriction. *

(3) Magnetization parallel to other axes produces values of magnetostriction between those for the [100] and [111] directions.



Magnetostriction of Single Iron Crystals (S. R. Williams), exhibiting discontinuities.

Fig. 17

b. Polycrystalline Materials

Bidwell[5] examined the magnetostrictive properties of some iron rings and found one that contracted for all values of the applied field, while most of the samples first expanded and then contracted for larger values of magnetizing force. In some later work, using iron rods for samples, the effect of tension on the values of magnetostriction demonstrated that simple loading of the specimen would cause material to show only the negative effect. This is illustrated in Fig. 6 from his work.

Honda and Shimizu[6], using a soft iron rod of unknown history, investigated the effect of temperature on magnetostriction. Temperature was varied from -186° C. to 818° C. The results are shown in Fig. 18.

It is to be noted that at temperatures below the Curie point, and at high values of H, the slope of the curve is the factor most affected by temperature. At the lower values of H in the range which is of interest in transformer design, there is no simple correlation of $\frac{\Delta L}{L}$ with temperature.

Dorsey[7], using iron rods of various known carbon contents, used $\frac{\Delta L}{L}$ maximum to obtain a correlation with

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5) Bidwell - Proc. Roy. Soc. 40 (1886), 109-257.

6) Honda and Shimizu - Phil. Mag. 6 (1903), 392-400.

7) Dorsey - Phys. Rev. Ser. 30 (1910), 698-719.

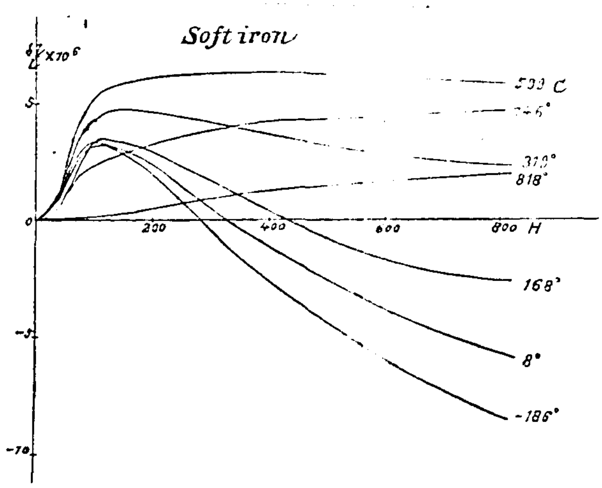
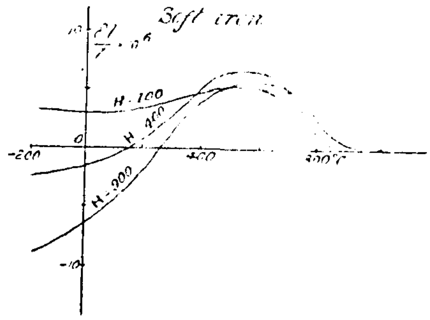


FIG. 7.



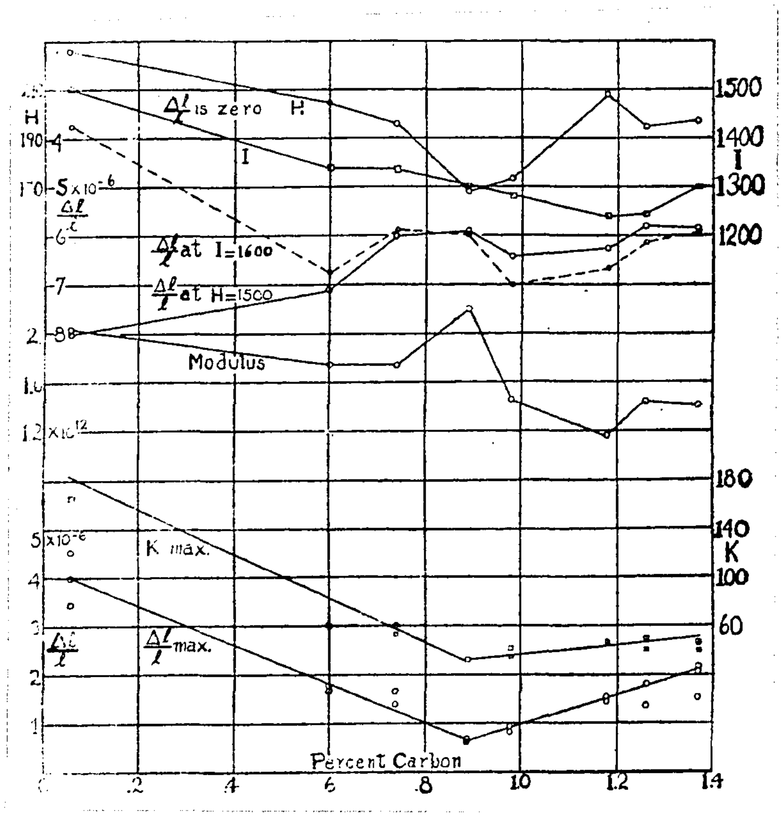
Magnetostriction of iron as a
function of temperature
(Honda and Shimizu).

Fig. 18

carbon content. This is shown in Fig. 19. The correlation is fairly satisfactory. Dorsey also is aware of the effects of cooling rates, but was unable to obtain consistent results with his quenching and annealing practice.

Schulze[8], using rod samples, conducted an extensive investigation of the relationship between

8) Schulze, Zf. Physik 50 (1928), 448-505.



Magnetostriction as a function
of carbon content (Dorsey).

Fig. 19

composition and magnetostriction. While the testing equipment was equipped to measure H and I, in numerous instances the measurement of I was neglected, and results in limited interpretation of these data. Fig. 20 gives the relationship between $\frac{\Delta L}{L}$ and H for various values of silicon. Attention is directed to the negative values obtained for 6.37% silicon.

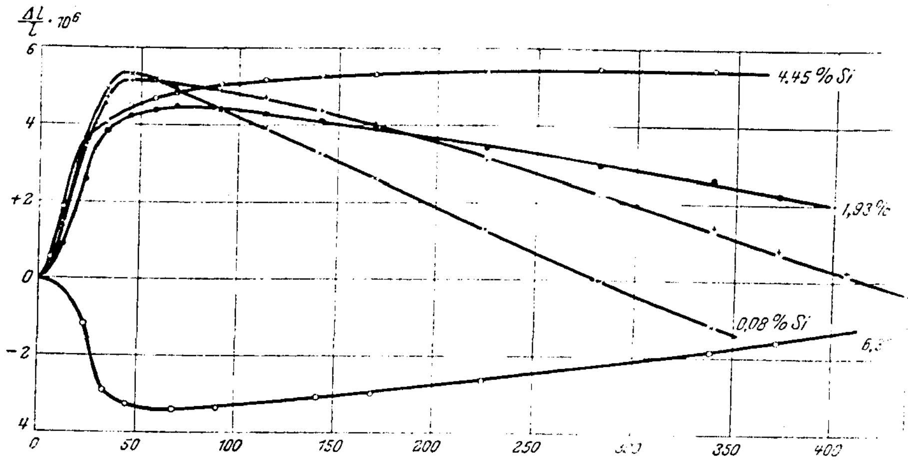


Fig. 26. Die Magnetostriktion der Eisen-Silicium-Legierungen in Abhängigkeit vom äußeren Magnetfeld.

Fig. 20

Fig. 21 presents the same data with silicon content as the independent variable. While curves are presented on the basis of constant H, I not having been determined,

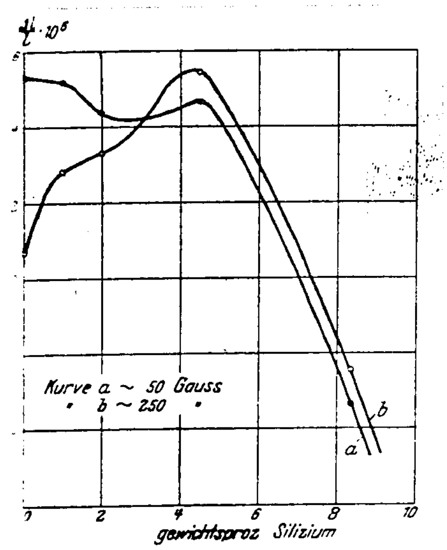


Fig. 27.
Die Magnetostriktion der Eisen—Silicium-Legierungen in Abhängigkeit von der Konzentration. (Kurven gleichen äußeren Magnetfeldes.)

Fig. 21

it is of interest to note the maximum values at about 4.5% silicon and zero values between 6.5 - 7.5% silicon, depending on the field strength, H. Alloys of greater silicon content were not investigated because of their poor mechanical properties. At silicon compositions above 6.0%, the material is exceedingly brittle at all temperatures, and therefore cannot be worked.

Figs. 22 and 23 represent a study of the iron-nickel alloys. Fig. 22 represents magnetostriction curves

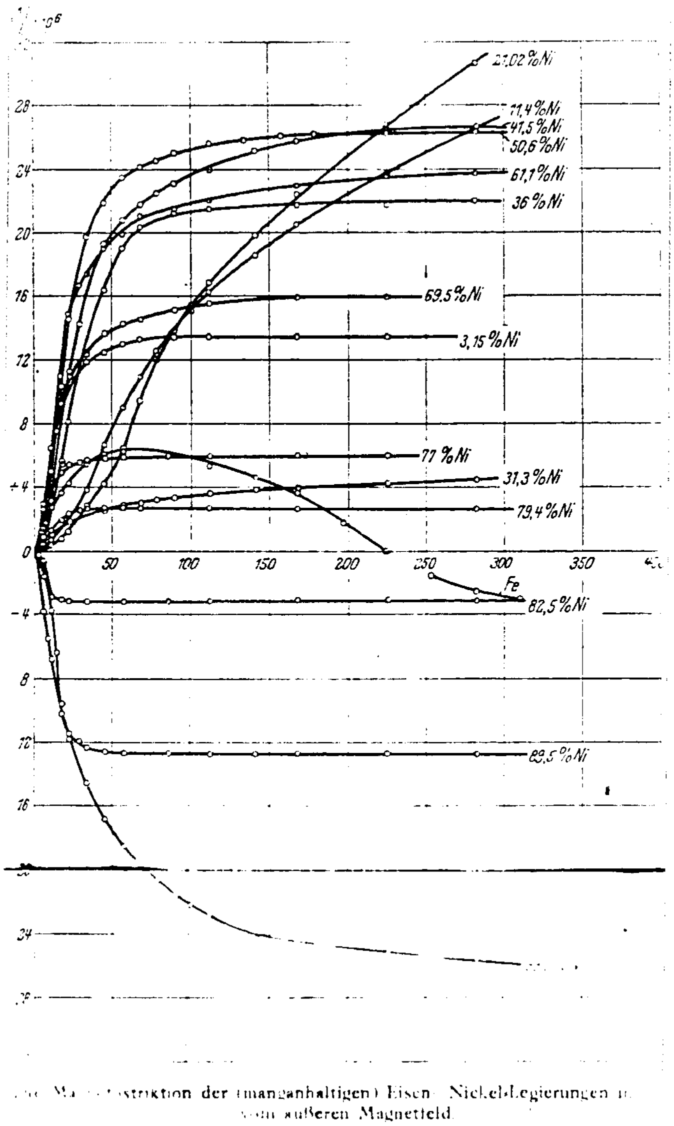
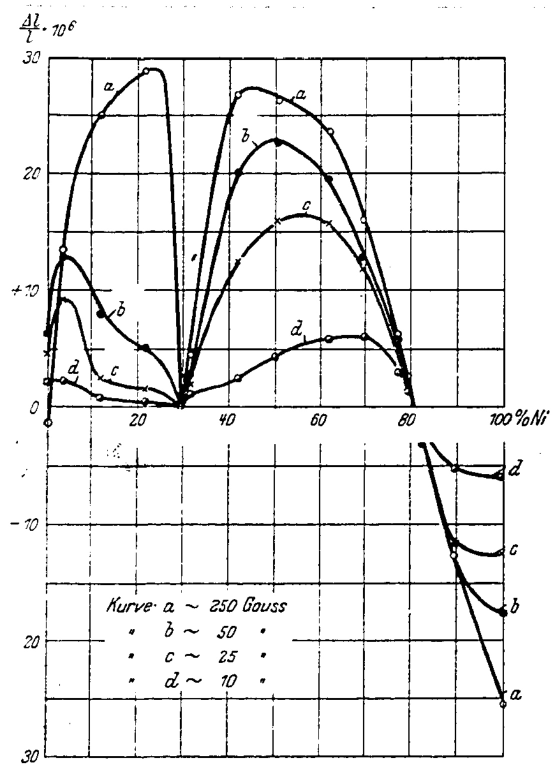


Fig. 22

Magnetostriction of Iron-Nickel Alloys as a Function of the Applied Field.



ie Magnetostriktion der (manganhaltigen) Eisen—Nickel-Legierungen in Abhängigkeit von der Konzentration. (Kurven gleicher äußerer Feldstärke.)

Fig. 23

Magnetostriction of Iron-Nickel Alloys as a Function of Composition.

with constant composition, and Fig. 23 is for constant applied fields. The permalloy composition, 80% nickel, 20% iron, has a zero value of magnetostriction for all values of H, the field strength.

In summation, it can be stated that the literature indicates three possibilities for the production of a low magnetostriction material, namely:

(a) Application of tensional stress to the material.

(b) The use of a suitable alloying element.

(c) Production of a material with such a grain orientation that magnetostriction will be reduced to a satisfactory level.

With the lack of data that could be used on the specific problem at hand, the need of a test method to measure magnetostriction on samples from commercial material was apparent.

5.0 - TEST EQUIPMENT AND PROCEDURE

The methods used for the measurement of magnetostriction are adequately reviewed in the literature[9, 10]. Review of these made the choice of the Wheddington[11] ultra micrometer logical. The method consists of allowing the change of dimension of the sample to vary the capacity of a parallel plate condenser. The change in capacity is then measured by a beat frequency method. The capacity of a parallel plate condenser is given by:

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9) Williams, S. R. - Magnetic Phenomena - McGraw Hill.

10) Bates, L. F. - Modern Magnetism - Cambridge Press, 1939.

11) Wheddington, R. - Phil. Mag. 40 (1920), 634.

$$C = \frac{.0885\ KA}{S} \qquad \text{(Eq. I)}$$

where C = Capacity in $\mu\mu$ farads

K = Specific inductive capacity of the dielectric (Air = 1)

S = Separation of the plates in cm.

A = Area of the plates in square cm.

The rate of change of C with respect to S in air is then

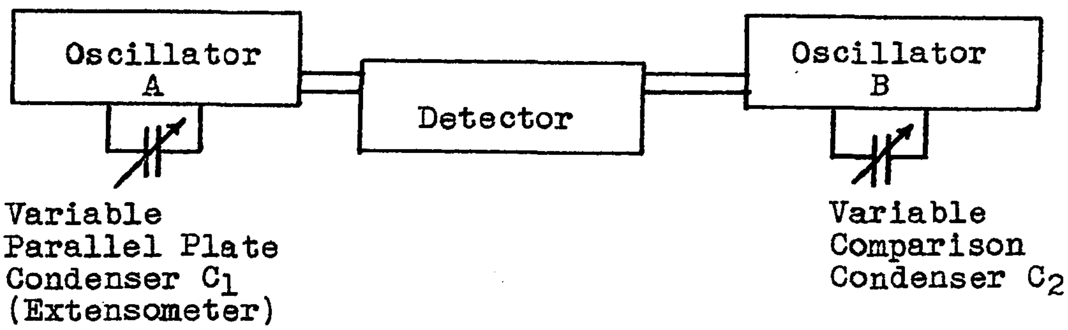
$$\frac{dC}{dS} = \frac{-.0885A}{S^2} \qquad \text{(Eq. II)}$$

This equation shows that the plates of the condenser must be operated as closely together as possible in order to obtain the largest change in capacity for a given change in spacing, dS.

To obtain a quantitative measurement of the capacity, a direct comparison with a standard is employed. The condenser is used as the capacitance in an electron-coupled oscillator operating at a high frequency. An oscillator of this type is very stable, being used quite often as a secondary frequency standard.

A second oscillator of the same type was constructed, its frequency being controlled by an ordinary movable plate type variable condenser. The capacitance is the comparison standard for the parallel-plate measuring condenser.

The high frequency oscillations were then fed on to separate grids of a vacuum tube detector. By means of head phones in the plate circuit, the two oscillators can be adjusted to the same frequency, i.e., zero beat, by suitable setting of the condensers. A block diagram of the components follows. A detailed wiring diagram is to be found in Appendix I.



The condenser C_2 was motivated by a vernier dial with 100 main scale divisions and a vernier having 10 subdivisions. Calibration of the comparison condenser C_2 was effected by substituting a General Radio Standard Variable Condenser for C_1. The middle portion of the scale on C_2 was found to be linear, with each vernier division corresponding to 0.106 uuf. During this calibration and subsequent checks, it was found possible to hold the zero beat condition for long periods after the equipment had been warmed up for approximately ten minutes. The Standard Variable Condenser was set at 600 μμf capacity for this calibration. The zero beat setting on condenser C_2 was exceptionally sharp; the change of 1 vernier division was easily detected.

The use of equation (II) and the assumptions (1), the change in capacity (ΔC = .106 μμf) is small compared with capacity, C (600 μμf), and (2) that the change in length ($\Delta S = 50 \times 10^{-8}$) is small compared with the parallel-plate spacing, S, the value of $\frac{A}{S^2}$ can be computed:

$$\frac{A}{S^2} = \frac{-.106}{50 \times 10^{-8} \times .0885} = \frac{1.06 \times 10^{-1} \times 10^{+8} \times 10^{-1}}{.4425}$$

$$A = 2.39 \times 10^{8}\, S^2 \qquad \text{(Eq. III)}$$

Assuming circular condenser plates

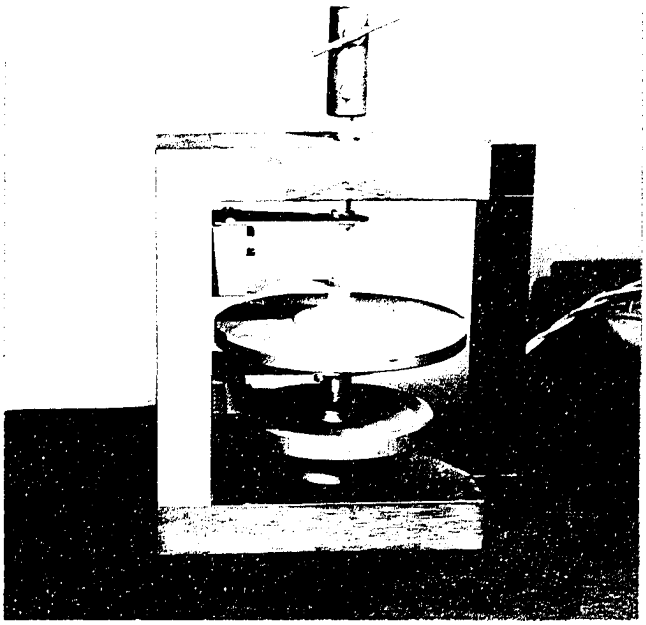
$$A = \pi r^2 = 3.1416\, r^2 \qquad \text{(Eq. IV)}$$

Rewriting Eq. III

$$r^2 = \frac{(2.39)}{\pi} \times 10^{8} \times S$$

$$S = .00115\, r$$

With careful design, it should be possible to set the parallel plates at .001 cm. In such an event, r could be 1 cm. However, as such a setting could be difficult and time-consuming, it was decided to make the plates with a 6 cm. radius. The mechanical design of the condenser C_1 passed through a number of variations; the final one is pictured in Fig. 24 and in the drawing in Appendix II.



Parallel Plate Capacitor for Use as an Extensometer.

Fig. 24

The features of the design are the plate fulcrum system for keeping the plates parallel without restricting the vertical movement of the upper plate and the jack screw for raising and lowering the bottom plate to the desired setting, S. This jack screw (.05 cm/rev) is activated by a collar with 60 engine-divided index marks on its periphery.

The extensometer can be calibrated by two independent methods (a) displacement of the lower plate through a known distance by means of the jack screw, (b) by substitution of a standard variable capacitance for the parallel measuring condenser C_1. Using the value of the capacitance determined by substitution and the area of the parallel plates determined by actual measurement, the value of S may be determined from Equation I. Substitution of this value in Equation II will give a value for $\frac{dC}{dS}$. For values of ΔS sufficiently small when compared with S

$$\Delta C = \left(\frac{.0885\ AK}{S^2} \right) \Delta S \qquad \text{(Eq. V)}$$

By the direct displacement, the calibration was determined to be 2.97×10^{-6} cm. per division, or 5.96×10^{-8} $\frac{\Delta L}{L}$ when a 50 cm. sample is used. The other method, substitution, gave a value of 3.02×10^{-6} per division, or 6.04×10^{-8} for $\frac{\Delta L}{L}$ when a 50 cm. sample is used. Details of these calculations are found in Appendix III. In all measurements the figure 6×10^{-8}/division was used for the calibration constant.

Examination of various types of magnetization equipment made it seem best to use a simple solenoid of sufficient length to provide a uniform field over its central portion. A coil 100 cm. long and 6.4 cm. inside diameter, consisting of 1,055 turns was wound on a Formica tube. Exploration of the field using an exploring coil demonstrated the field to be in agreement with the values calculated from

$$H = \frac{.2\,\pi\, ni}{L}\,(\cos\theta_2 - \cos\theta_1)$$

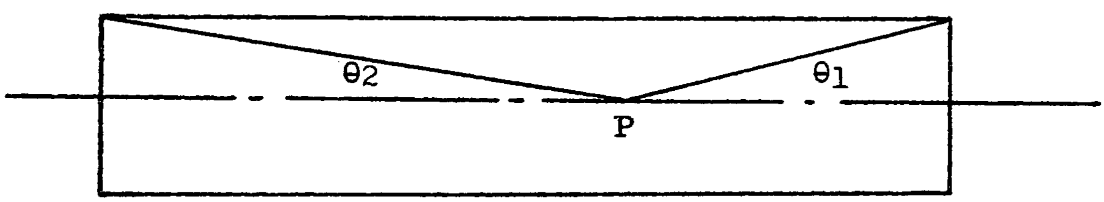
where H = Field in gauss

n = Number of turns

i = Current in amperes

L = Length of the coil

θ = the angle with the vertex on the axis of the coil and whose sides are defined by the axis of the coil and a line from the point under consideration, P, and the end turn of the coil. Subscript 1 is used for the angle at one end and 2 for the angle subtended at the other.



The value of the ferric induction, B, produced in the sample, was determined from a 200 turn search coil wrapped on a plastic form. This coil is slipped over the sample before it is mounted in the magnetizing coil. The induction, B, was measured by the deflection of a ballistic galvanometer. Using values of B determined by the ballistic galvanometer and values of H calculated from current measurement, values of the permeability, μ, could be determined within 2% of those determined on the Fahy Simplex Permeameter. The magnetizing coil was mounted in the vertical position on L-shaped frame made of wood with the parallel plate condenser resting on the foot of the L. A brass stud was mounted at the upper end of the wooden L to support the sample in the coil. The sample support system was constructed out of 1/4 inch aluminum rod. A universal joint was placed in the support rods, one above and the other below the sample to minimize the restraint imposed on the specimen while under test. The sample and the support system were assembled on a jig before introduction into the coil. Photographs in Figs. 25 and 26 illustrate these points.

The great distance between the end of the coil and the parallel plate condenser was found to be necessary to avoid coupling between the magnetizing coil and the condenser through their electro-magnetic fields. The distance employed was arrived at by fixing the plates of the parallel condenser at a standard setting and with a sample in place but with the driving rod disconnected from the movable plate and then applying the field H to the sample. If the condenser were in the field of the

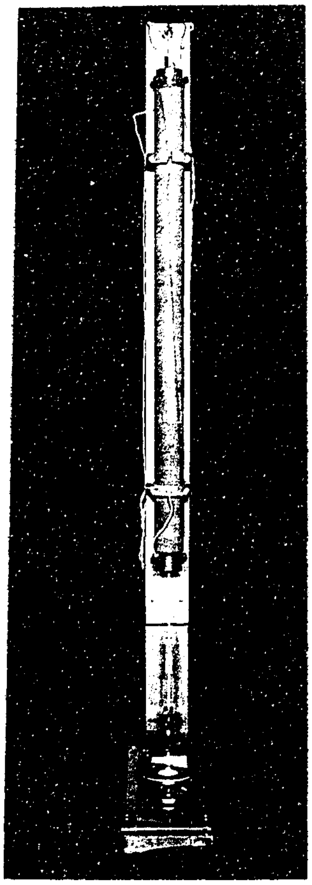


Fig. 25

Illustration of magnetization unit showing relation of component parts.

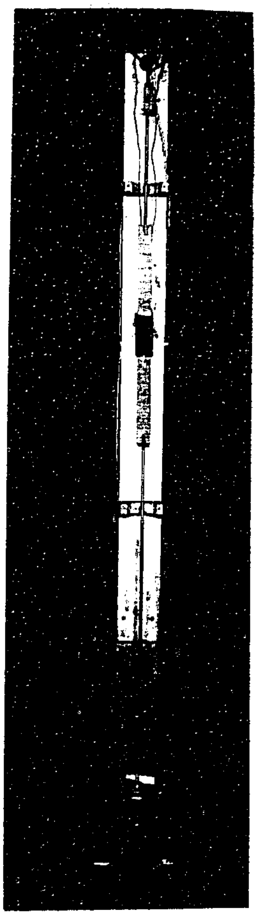


Fig. 26

Illustration with magnetizing coil removed to show sample and supports.

magnetizing coil, the beat note would be affected. The distance used in the construction of the test unit is sufficiently large so that no effect could be observed by this technique.

Vibration from surrounding equipment and movement of personnel in the vicinity of the test frame caused the beat note to wobble and drift as did the slight changes in temperature of the room in an air-conditioned building. These effects were minimized by supporting the test frame from sponge rubber supports in a 3/4 inch pine box ("coffin"). This is pictured in Fig. 27. While the drift of the zero beat condition was still noticeable, it was reduced to such a point that it did not interfere with the determination. The change in length due to magnetization is instantaneous and can be followed so closely by the measurement that a slow temperature drift is not noticeable. The drift could be canceled out by making one measurement when the field is applied, and another when it is removed, and averaging the two values. It was found, however, that the change in the length was independent of the initial state, that is, with zero H magnetized or demagnetized. The reasons for demagnetization making no difference in the magnetostriction values obtained are:

(a) The material is magnetically soft and so demagnetizes easily.

(b) Very little, if any, magnetostriction takes place at values of B below the residual value, B_r.

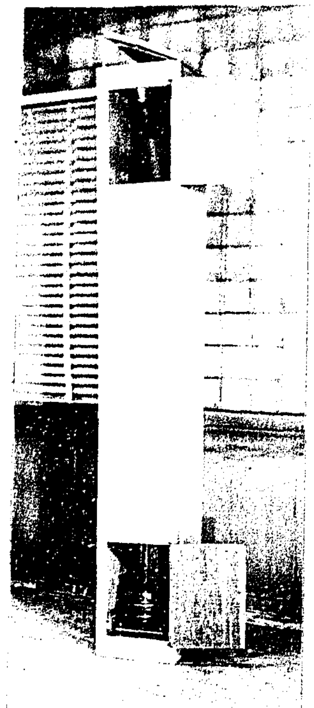


Fig. 27

Illustration of pine box (coffin) used as a thermostat to reduce temperature drift.

With this equipment, it is possible to make a determination in approximately ten minutes. The greater portion of this time is consumed in setting the ferric induction, B, by means of the ballistic galvanometer.

The test is reproducible to within $\pm 25 \times 10^{-8} \frac{\Delta L}{L}$ on flat samples. Samples that were not flat or had not been handled carefully would not give satisfactory results, i.e., could not be reproduced. The equipment is very satisfactory for comparison studies, but is not satisfactory for an absolute standard because the ferric induction in the sample is not uniform.

6.0 - EXPERIMENTATION

Transformer fabricators were designing their power transformers to operate at a ferric induction, B, in the range 13.5 - 15.0 kilogauss when this investigation was undertaken. If necessary to meet a particular noise specification, the induction could be dropped to 12.8 kilogauss. At any value of induction the value of $\frac{\Delta L}{L} = 185 \times 10^{-8}$ would allow the most stringent noise specification to be met. With these figures in mind, a survey of magnetostriction in the highest grade transformer steel was undertaken.

6.1 - SAMPLES

Two sheets of transformer steel of known history were selected before the final high temperature anneal. The analysis of the material when the steel was poured into the ingot molds showed 4.80% silicon and .035% carbon, which is "normal" for these materials. Core loss tests on samples from this lot of material gave .50 watt/pound at 10 kilogauss. The Erichsen number (a ductility index) was 3 mm., which is also within the usual range. One sheet of material was given the regular high temperature, controlled atmosphere anneal, which is standard mill practice. The other was kept in the unannealed or "green" condition for control purposes. These sheets were 29 gage (.014"), 25 x 100 inches. The end of the annealed sheet was cut off so as to remove the blue oxide border formed during box annealing and thus eliminate any possibility of having a variation of magnetostriction in the samples because of an end effect. From this cut end, two sections 50 cm. long were sheared with the measured dimension parallel to the rolling direction. Each of the 50 cm. by 25 inch sections was split into 50 x 3 cm. Epstein samples with the 50 cm. direction parallel to the rolling direction. As the final cut was made the samples were numbered from 1 to 21 consecutively across the sheet. One series of 21 samples had the suffix "R" attached to the numbers so that the two series from the one sheet could be differentiated. Another series of Epstein samples was sheared in a similar manner from the "green" sheet and had the suffix "G" attached to the numerical designation. These three sets of samples will be designated as series one (Sr. 1) and Series R (Sr. R) and Series G (Sr. G), respectively.

6.2 - EXPERIMENTS

Magnetostriction measurements were made on the strips of Sr. 1 with varying amounts of tension; namely, 1040 grams and 3040 grams. In addition, samples 1, 5, 9, 13, 17, and 21 were tested with 4660 grams. All the aforementioned tests are presented graphically in Fig. 28, Curve 3224 (curves (a), (b), and (c), respectively).

The conclusions drawn from these data are:

1. There is ten-fold variation in the sheet as processed commercially.

2. Application of tension reduces magnetostriction.

3. Tensional stresses tend to make the variation of this property within the group of samples smaller.

All even-numbered strips in Sr. 1 were then hydrogen annealed in a sealed tube type of electric furnace for thirty hours at 2200° F. with a dry hydrogen atmosphere. These strips were coated with magnesia to prevent

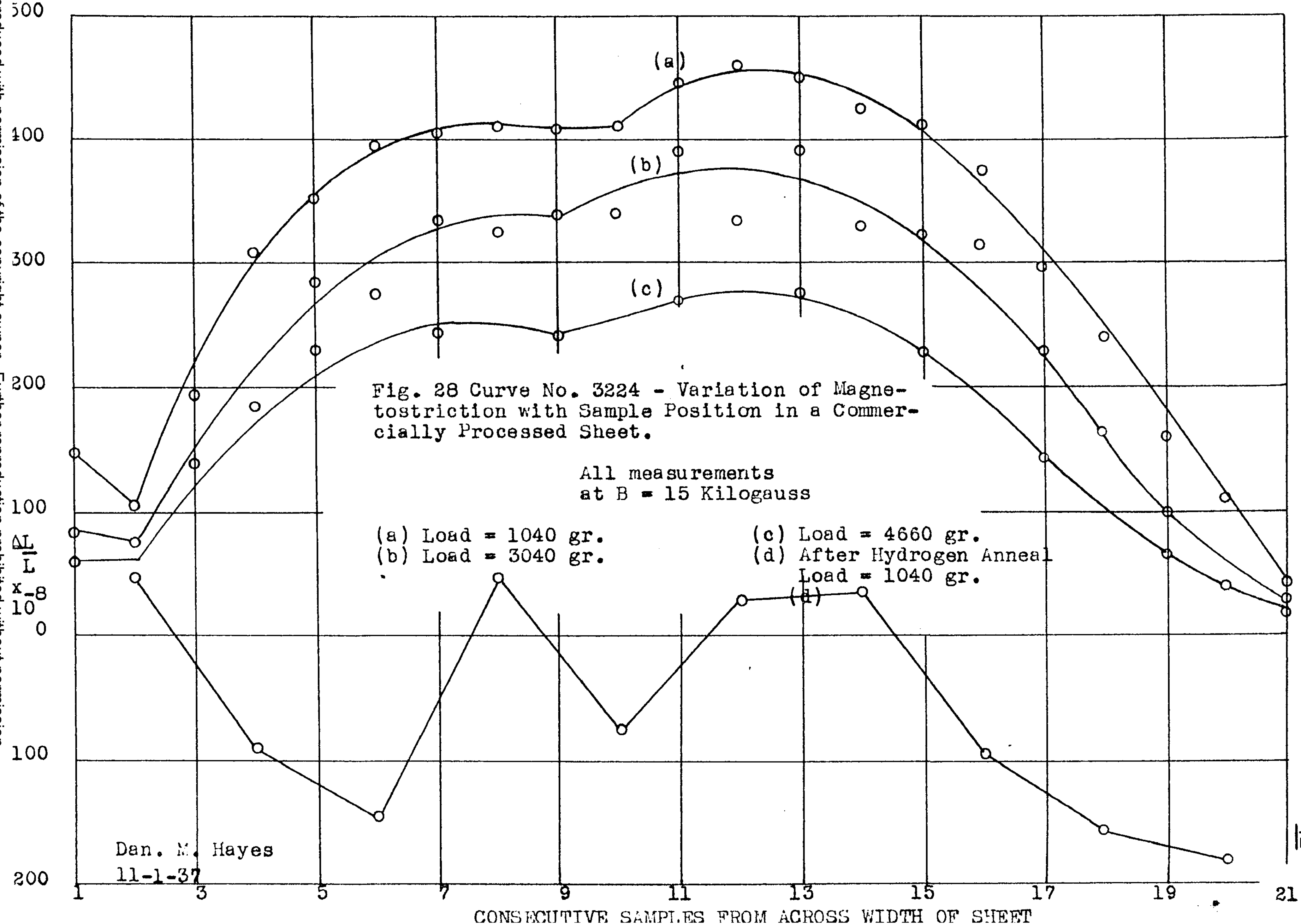


Fig. 28 Curve No. 3224 - Variation of Magnetostriction with Sample Position in a Commercially Processed Sheet.

sticking. On Curve No. 3224 (d) the results of the magnetostriction tests after annealing are presented. These tests were run at B=15,000 gauss and under a load of 1040 grams. It is to be noted that this processing, in the majority of the cases, gives a material with the desired magnetostriction characteristics ($\pm$ 185 x 10^{-8} $\frac{\Delta L}{L}$ at B=15,000 gauss). Of the ten samples so treated, seven are in the desired range, while all are in the range +50 to -200 $\frac{\Delta L}{L}$. The curve representing these values is drawn as a broken line because there now seems to be little or no functional relation between the magnetostriction and the position of the sample in the sheet.

The samples of Sr. G and Sr. R were coated with magnesia and given the same hydrogen anneal as described above. Representative strips from these two groups of samples were tested at B=15,000 gauss with a load of 1048 grams and 3048 grams. The broken line curves Nos. 3226 (Fig. 29) and 3227 (Fig. 30) again demonstrate the lack of functional relation between magnetostriction and the position of the sample in the sheet. It is to be noted, however, that the values obtained from Sr. R are much lower than those of Sr. G. All values for the R series are negative while those of the G series have both positive and negative values. The

Fig. 29 Curve No. 3226
Variation of Magnetostriction with Sample Position in a Commercially Processed Sheet after Hydrogen Anneal as Epstein Strips.

Curve (a) - Load = 1040 gr.
Curve (b) - Load = 4660 gr.

Dan M. Hayes
11/20/37

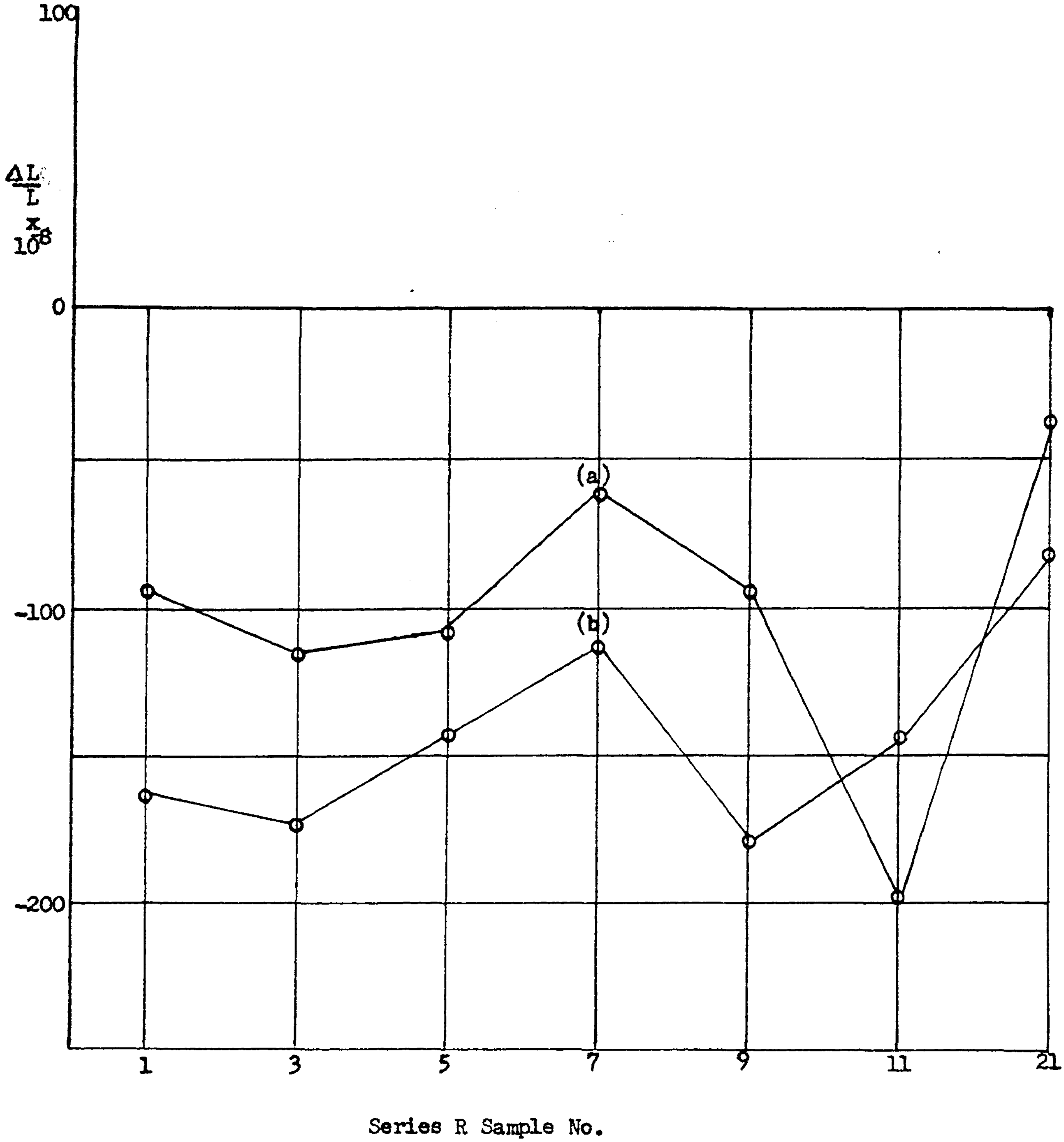
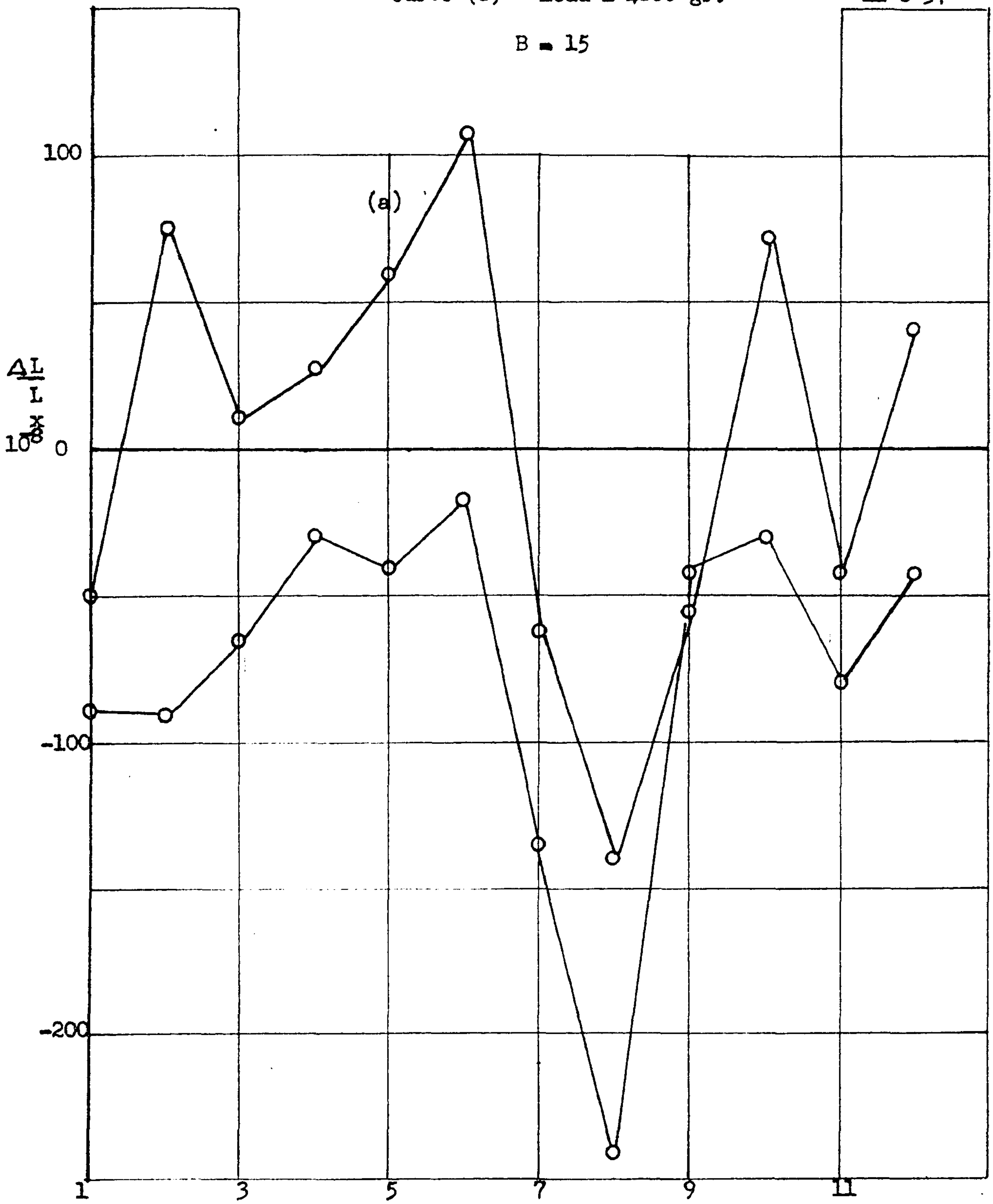


Fig. 30 Curve No. 3227
Variations of Magnetostriction with Position in the "Green" Sheet after Hydrogen Anneal as Epstein Strips

Curve (a) - Load = 1040 gr.
Curve (b) - Load = 4660 gr.

Dan M. Hayes
11-6-37

B = 15



Series G Sample No.

generalizations that may be made from these experiments are:

1. Hydrogen annealing, as practiced at the Research laboratory, produces a material of relatively low magnetostriction as compared with the plant processed material.

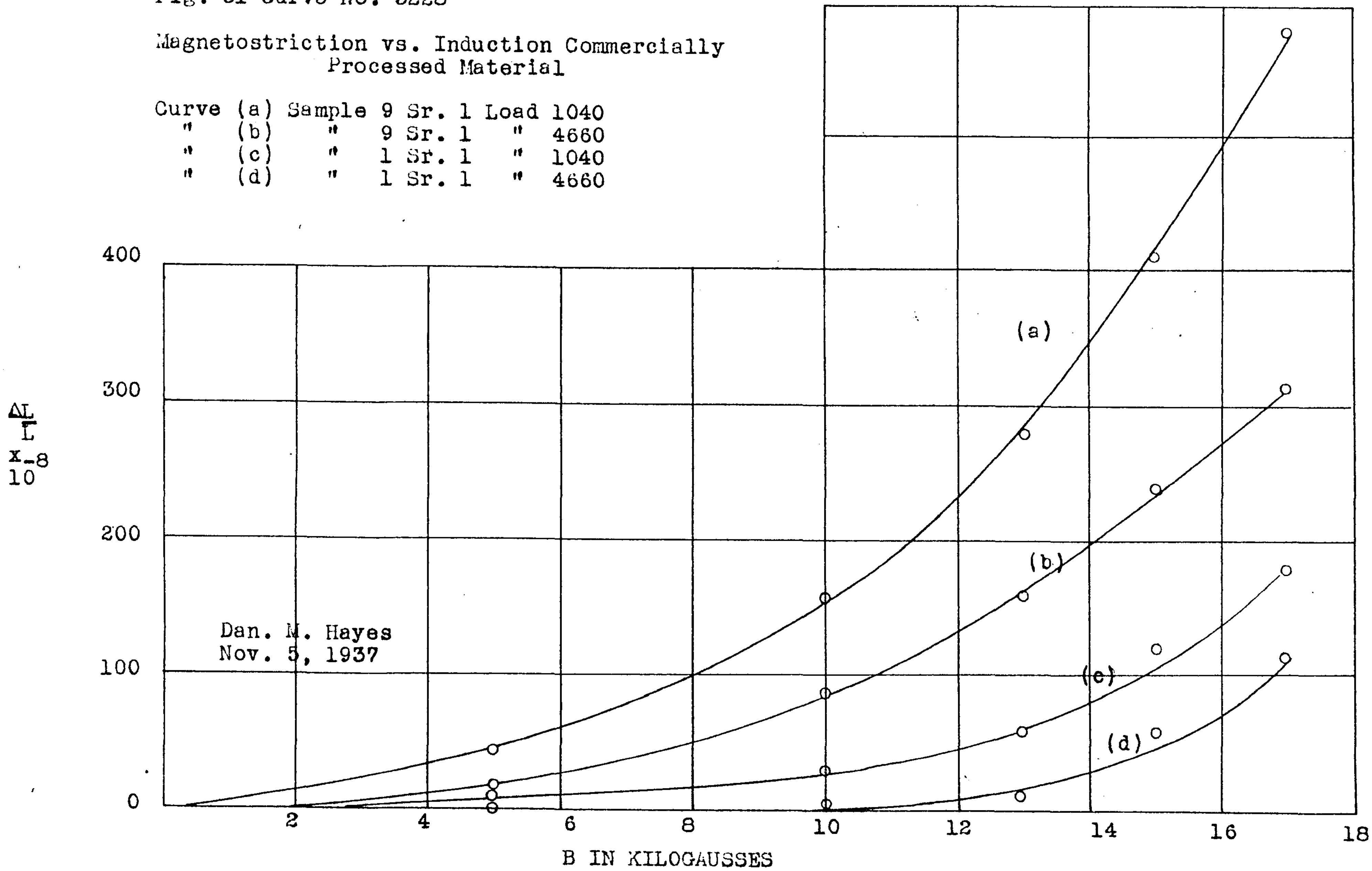
2. Hydrogen annealing in narrow widths destroys the uniform variation of magnetostriction shown by the same material when annealed in wide widths.

3. Elastic tensional deformation in the direction of the applied magnetic field will usually make magnetostriction take on a more negative value.

After observing the great variation between center and edge samples in Sr. 1, it was decided to obtain data which would describe the variation of magnetostriction with induction in a sample belonging to the two groups. Samples 1 and 9 from Sr. 1 were tested with 1040 and 4660 grams tension with the induction varying from 0 to 17,000 gauss. The results shown in Curve No. 3228 (Fig. 31) demonstrate that the curves for these two samples have the same general characteristic shape, differing probably by a tensional factor.

Fig. 31 Curve No. 3228

Magnetostriction vs. Induction Commercially Processed Material



As negative values did not develop in the case of the experiment mentioned in the previous paragraph, the same experimental procedure outlined was used on a sample that was known to have negative magnetostriction, namely, No. 21, or Sr. R.

Fig. 32, curve (a), is the result of the test with a load of 1040 grams, while Curve No. 3225-(b) has a tensional load of 4660 grams. While these curves have negative values, no evidence so far presented demonstrates that the application of tension will cause a sample with positive magnetostriction to take on negative values. Curves Nos. 3225-(c) and 3225-(d) demonstrate that it is possible to cause the positive phenomenon to become negative by the simple application of tension. These curves were obtained by testing sample No. 21, Sr. R, after abrading the surface with emery cloth. The sample lost .4 gram, or 1%, of its weight during this process. Because abrasion raised the magnetostriction values, it was decided to observe the effect of carrying this procedure further. Sample No. 21, Sr. G, was abraded with emery cloth again with a percentage weight loss of 1.3%. After this treatment, it was again tested with two tensional loads, namely, 1040 grams and 4660 grams. The surface of the strip was still pitted and dull in some places. To brighten all of the surface

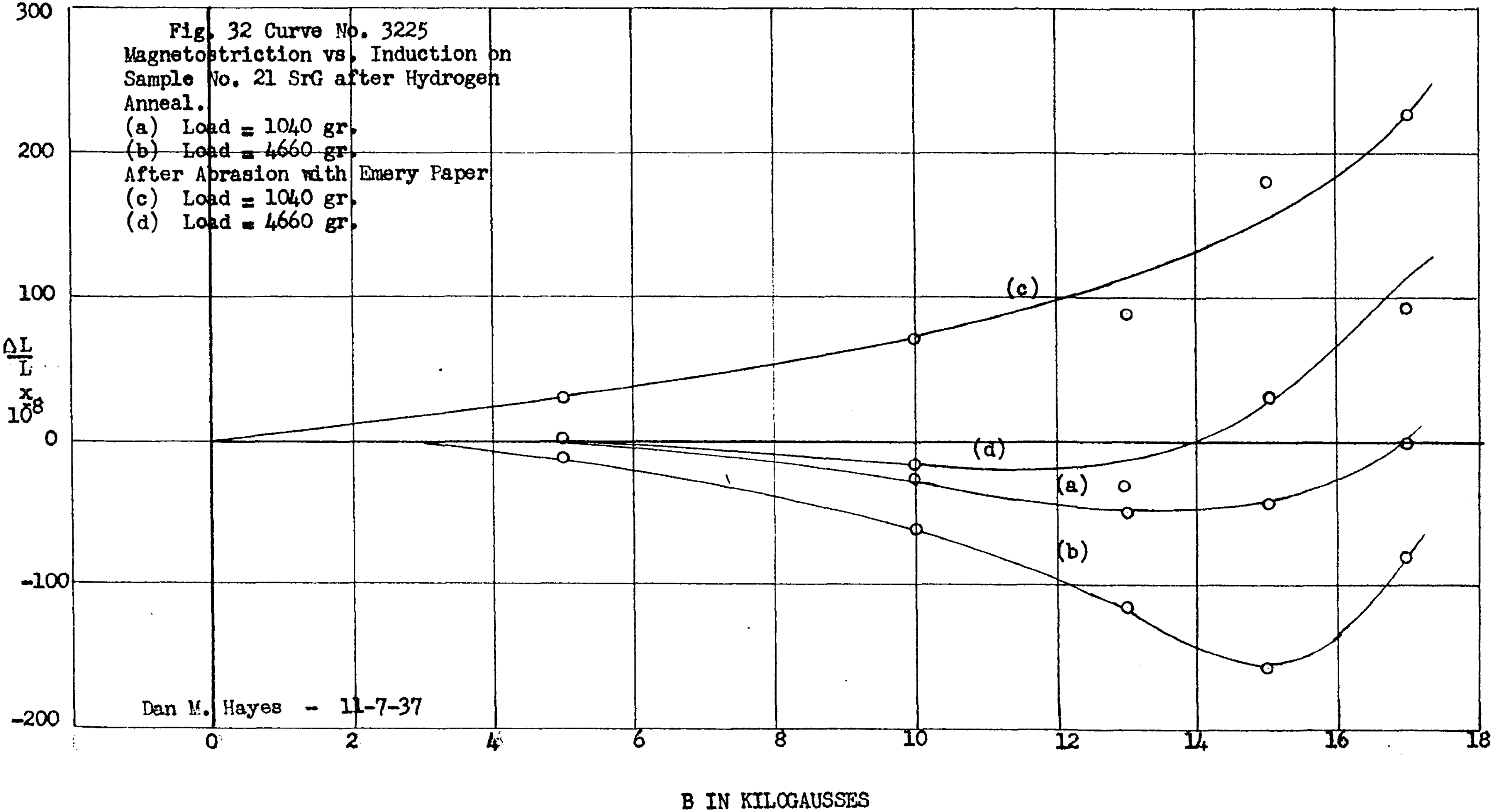


Fig. 32 Curve No. 3225
Magnetostriction vs. Induction on Sample No. 21 SrG after Hydrogen Anneal.
(a) Load = 1040 gr.
(b) Load = 4660 gr.
After Abrasion with Emery Paper
(c) Load = 1040 gr.
(d) Load = 4660 gr.

and remove a greater amount of metal, an air grinder was substituted for the emery cloth in the third abrasion. In this last grinding the strip lost 3.9% of its original weight. Again it was tested with two tensional loads at various inductions. While making these tests, it was observed that the permeability had been appreciably lowered, especially at the lower magnetizing forces. The data obtained in these tests are presented in graphical form in Curve No. 3229 (Fig. 33).

Again all positive curves show the same characteristic difference, but the negative curves have taken on different shape at the higher inductions. This is not surprising, as negative magnetostriction would not necessarily be explained by the same functional relation as the positive phenomena. It is conceivable that new factors make their appearance as soon as magnetostriction becomes negative. The generality demonstrated here is that by the proper choice of tensional stress, it is possible to obtain control of magnetostriction. Predicting from Curve No. 3229, one should be able to keep magnetostriction within the range $\pm$ 185 x 10^{-8} $\frac{\Delta L}{L}$ when the induction is varying from 0 to 20 kilogauss.

After these results were obtained by means of surface abrasion, it was decided to attempt the removal of the surface of similar test strips by pickling. The

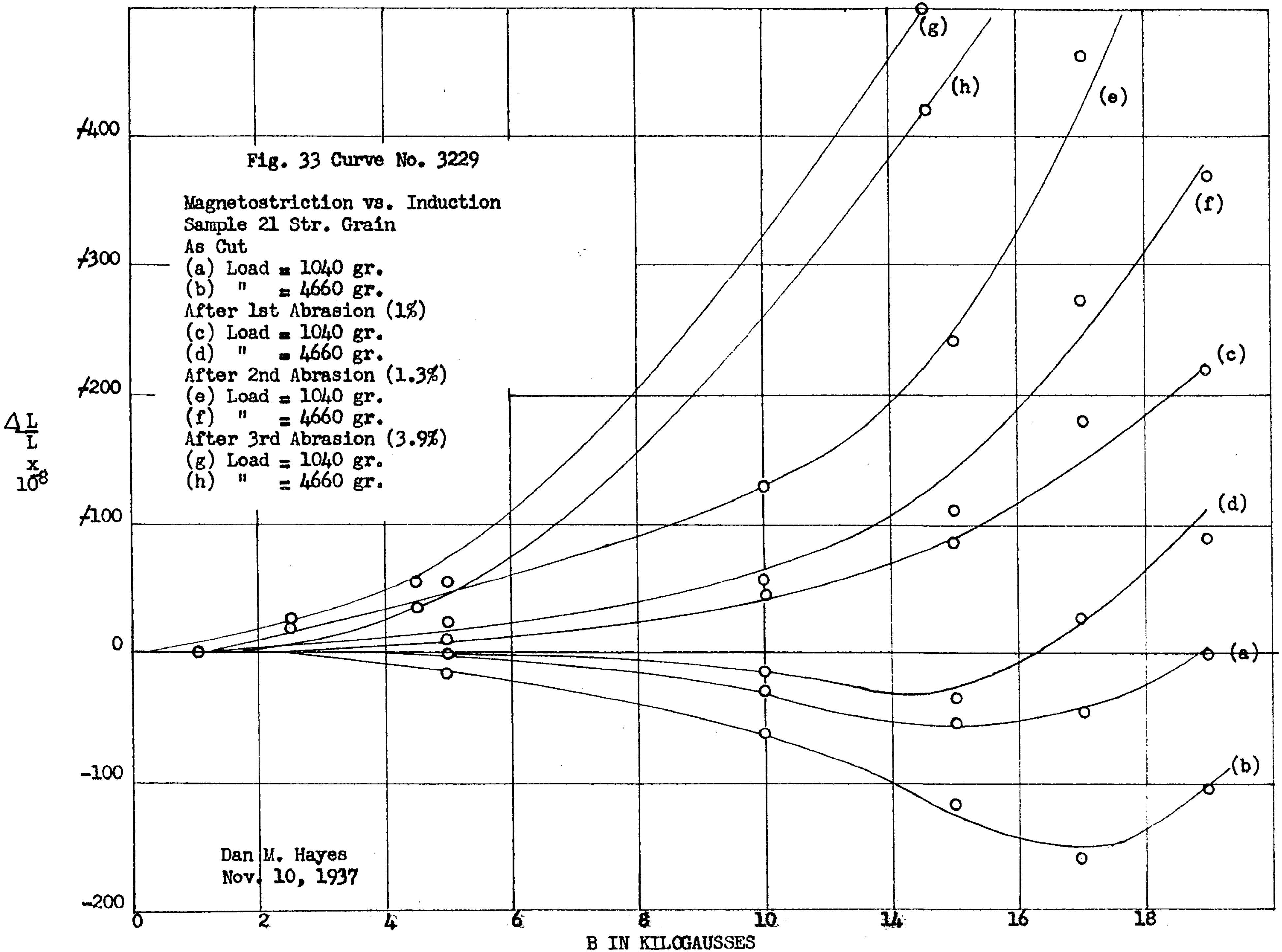


Fig. 33 Curve No. 3229
Magnetostriction vs. Induction
Sample 21 Str. Grain
As Cut
(a) Load = 1040 gr.
(b) " = 4660 gr.
After 1st Abrasion (1%)
(c) Load = 1040 gr.
(d) " = 4660 gr.
After 2nd Abrasion (1.3%)
(e) Load = 1040 gr.
(f) " = 4660 gr.
After 3rd Abrasion (3.9%)
(g) Load = 1040 gr.
(h) " = 4660 gr.
Dan M. Hayes
Nov. 10, 1937
ΔL/L x 10^8
+400
+300
+200
+100
0
-100
-200
0
2
4
6
8
10
14
16
18
B IN KILOGAUSSES
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

hope was that pickling would give the same results as the abrasion treatment. As various investigators have been very successful in obtaining uniform pickling by means of electrolytic methods, strip No. 6 of Sr. 1 was chosen as a test piece and two attempts made to remove the surface by electrolytic pickling. Both attempts were failures, as the Tran-Cor coat could not be penetrated or dissolved under the conditions of the experiment. In places where this coat was not continuous, holes were eaten in the strip, but otherwise no pickling action was observed. After this failure, it was suggested that the use of a solution of 10% sulphuric acid and 4% hydrofluoric acid along with an inhibitor might remove the surface evenly without affecting the base metal. A trial experiment on the No. 6 test strip demonstrated this method to be feasible. Strips No. 20, 18, 16, and 14 of Sr. 1 were then given this treatment following the previously mentioned hydrogen anneal. All strips lost about the same amount of weight, namely, .5 gram, or 1.3%. Since the grain pattern had not been developed in the first pickle, the strips, with the exception of No. 20, were etched with a 10% solution of hydrochloric and nitric acids in the ratio of 3 to 1. The percentage weight loss on strips No. 14, 16, and 18 was, respectively, 13.8%, 11.4%, and 14.3%. Magnetostriction test results at B=15,000 gauss with a load of 1048 grams follow:

Sample No. Sr. 1	Magnetostriction $\frac{\Delta L}{L} \times 10^{-8}$ Commercially Processed	After H_2 Anneal	After 1st Pickle	After 2nd Pickle
20	108	-180	-42	Not pickled
18	240	-156	-90	-132
16	378	-96	+30	-66
14	420	+36	+168	+30

The data shown in the table are certainly not in agreement with the data obtained from the abrasion experiments. This simply means that the removal of metal by pickling is not the same as the removal of metal by abrasion. The primary difference in these two operations is the cold working of the surfaces in the case of abrasion.

It was decided to attempt to separate the variables in the hydrogen anneal so as to learn the necessary conditions for the production of a low magnetostriction material. These variables may be tabulated as follows:

1. Magnesia Coating
2. Atmosphere
3. Sample Width
4. Temperature

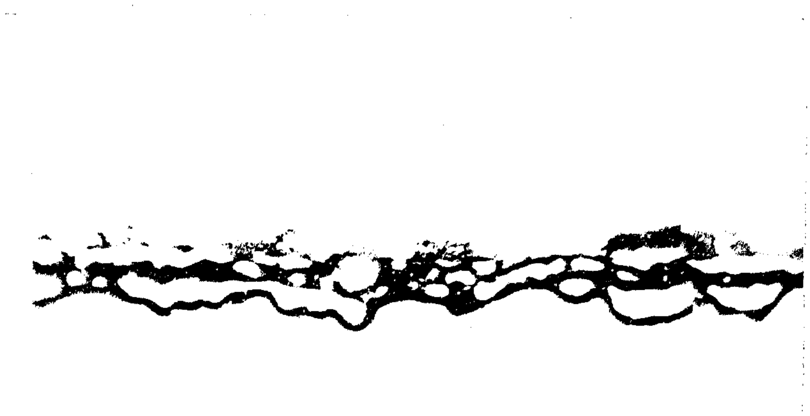
Strips Nos. 3, 5, 7, and 13 of Sr. 1 were hydrogen annealed without the magnesia coating. The magnetostriction results after the annealing were +36, -132, -180, and -96, respectively. These results are comparable with the values reported on Curve No. 3224-(d). As these materials are comparable and had identical treatment, with the exception of the magnesia coating, it is assumed that the magnesia is not the prime factor in the reduction of magnetostriction during a hydrogen anneal.

To obtain a partial answer to the question of the necessity for the hydrogen atmosphere, the strips mentioned in the previous paragraph, and in addition, Strips Nos. 11, 17, and 19 from the same series in the "as cut" condition, were placed in a double wrapper of Ingot Iron and annealed at 2200° F. for one hour. The samples were then allowed to cool with the furnace and then tested. The results are tabulated below:

	Magnetostriction $\frac{\Delta L}{L} \times 10^{-8}$		
Sample No.	Before Anneal	After Anneal	Change
3	+ 36	+150	+114
5	-135	+ 60	+195
7	-180	+156	+336
13	- 96	+162	+258
11	+450	+ 60	-390
17	+300	+130	-170
19	+165	+ 78	- 87

From this table it is to be concluded that annealing will erase most of the variation in magnetostriction across the width of a single sheet, but will not produce the small positive and the negative values associated with the hydrogen anneal. These conclusions are deducible from the facts that all high values of magnetostriction became smaller, while all the negative values became larger.

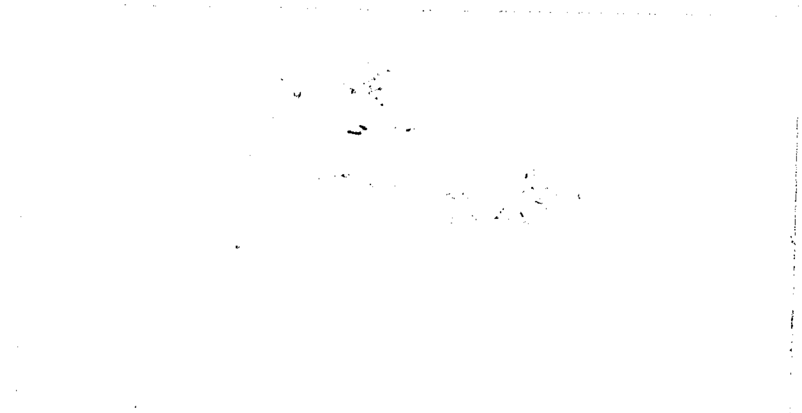
Because hydrogen annealing lowers magnetostriction, one may be led to believe that the anneal causes elastic stresses to be set up between the outer surfaces and the body of the material. If this were true, such a "skin" might be observable under a microscope. To see if this was the case, strips representing the center and edge of the sheet from each series (1, G, and R) were selected and prepared for microscopical examination. This preparation included copper plating before mounting to insure the surface of the metal from being disturbed during the polishing operation. Photomicrographs were then made at a magnification of 1000x. These pictures, with the corresponding magnetostriction results and sample history, are shown in Fig. 34. The obvious correlation between the pictures and magnetostriction is due to the relative thickness of a black layer between the copper and base metal; the thicker the layer, the lower the magnetostriction. The same strips used for microscopical examination had the surface (.0005") removed with a metal grinding cone. The resulting surface particles were then analyzed for total oxides, silica, alumina, and metallic iron. No definite



Sample 1 - Sr. 1
M-19820 - 1000x

$\frac{\Delta L}{L} = 120 \times 10^{-8}$

Estimated thickness of surface layer = .0003 in. Edge of commercially processed hot roll sheet.



Sample 9 - Sr. R
M-19821 - 1000x

$\frac{\Delta L}{L} = 414 \times 10^{-8}$

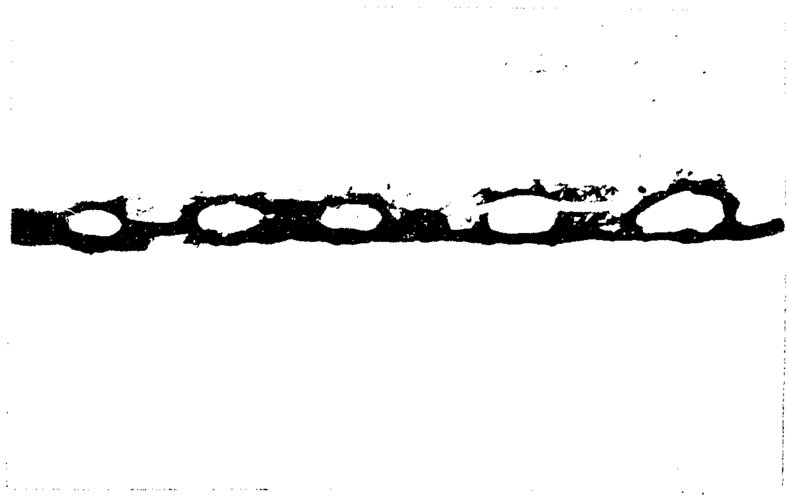
Estimated thickness of surface = 0 in. Center of commercially processed hot roll sheet.

Sample 1 - Sr. R
M-19824 - 1000x

$\frac{\Delta L}{L} = -95 \times 10^{-8}$

Estimated thickness of surface layer = .00025 in. Edge of commercially processed hot roll sheet after coating with MgO and hydrogen anneal in Epstein strips.

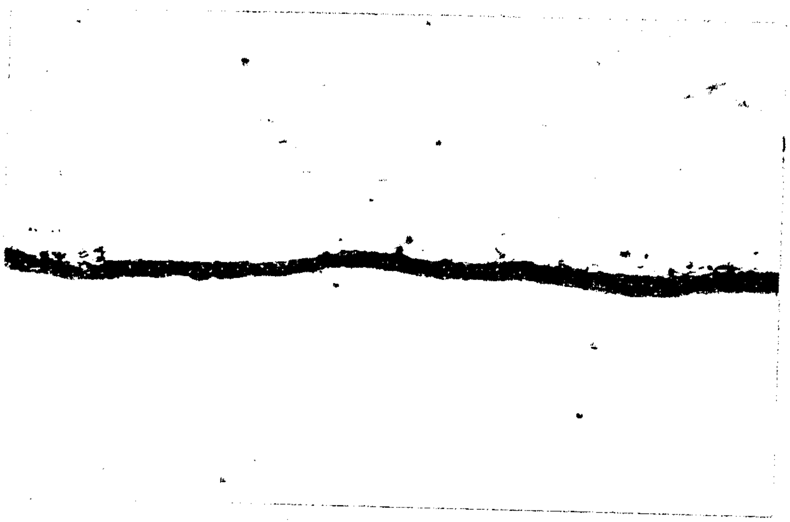
Fig. 34



Sample 7 - Sr. R
M-19825 - 1000x

$\frac{\Delta L}{L} = -60 \times 10^{-8}$

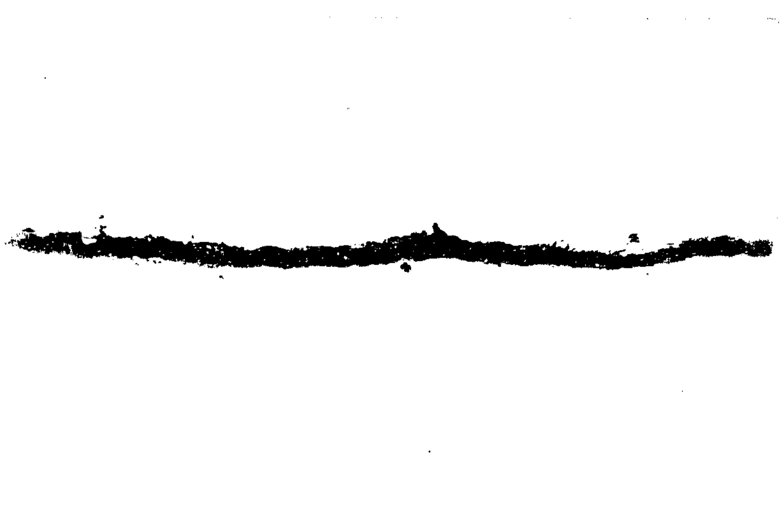
Estimated thickness of surface layer = .00025 in. Center of commercially processed hot roll sheet + MgO coat + hydrogen anneal as Epstein strips.



Sample 2 - Sr. G
M-19822 - 1000x

$\frac{\Delta L}{L} = 70 \times 10^{-8}$

Estimated thickness of surface layer = .00009 in. Green commercially hot roll sheet + MgO coat + hydrogen anneal.



Sample 10 - Sr. G
M-19823 - 1000x

$\frac{\Delta L}{L} = 70 \times 10^{-8}$

Estimated thickness of surface layer = .00009 in. Green commercially hot roll sheet + MgO coat + hydrogen anneal.

relationships can be pointed out between these analyses and magnetostriction. The chemical results are tabulated below:

Series	Sample	Chemical Analysis of Surface % Total Oxides	% SiO_2	% Al_2O_3	% Fe	$\frac{\Delta L}{L} \times 10^{-8}$
1	1	1.56	.60	.96	82	120
1	9	..10	.10	0	91	414
R	1	1.14	.50	.64	79	-60
R	7	.26	.18	.08	86	-95
G	2	.14	.10	.04	89	70
G	10	.22	.18	.04	90	70

6.3 - CONCLUSIONS

The conclusions that may be drawn from the experiments with a fair degree of certainty are:

1. Application of tensional stresses will algebraically lower positive magnetostriction.

2. The variation of magnetostriction in a sheet may be explained on the basis of differences in elastic tensional stress.

3. Surface abrasion will cause magnetostriction to algebraically increase.

4. A given sheet of material as processed commercially may be expected to have a variation in magnetostriction of from six to ten fold.

5. Hydrogen annealing of Epstein strips will usually yield a product of relatively low magnetostriction.

6. By proper control, the limits of $\pm 185 \times 10^{-8}$ $\frac{\Delta L}{L}$ at 15,000 gausses may be obtained.

On the basis of the experiments performed, it was postulated that the stress condition of the material is the fundamental variable in the magnetostriction characteristics of the transformer iron. There is, on the surface, a film that has a high electrical resistivity. This film is composed of CaO, SiO_2, and the oxides of iron, and has some of the physical properties of a glass. The film supports the section of the sheet in tension. The variation in magnetostriction observed by the application of tension to the test specimen supports the postulate directly. The removal of the surface film by all types of pickling, either acid or base, causes the magnetostriction of the sample to increase. Moreover, the removal of the film from one side of a test specimen caused it to take on a curvature with the pickled surface on the concave side, illustrating that the surface material had been subjected to compressive forces, or that existing tensional stresses had been relieved.

Similarly when the surface film is removed from one side of a sample by abrasion, the strip takes on a uniform curvature with the abraded surface being concave. While abrasion of the surface not only effects the removal of material but produces a certain amount of cold-work in the specimen itself, the relief of the film stress is apparent in the results obtained, and thus supports the postulate.

The wide variation in the magnetostriction values obtained within a single sheet of commercially processed material is the result of the final high temperature box anneal. An analysis of the temperature flow going into and from the charge of a box is very complex. However, it is known that a stack of sheet material has a much greater thermal conductivity in the planes parallel to the main surface of the sheets, and has a very small conductivity perpendicular to this surface. This is caused by the discontinuity and the presence of a more or less refractory material at the surface of each sheet. As a result, in a box anneal the sheet is heated and cooled primarily from the edges, and results in quite large temperature gradients being present during the cycle.

In the high temperature anneal in hydrogen, the samples are of Epstein size and so are not subjected to very large temperature gradients during heating or cooling as compared to a stack of sheets in a box anneal. It is proposed that these gradients are of such a nature as to produce the non-uniformity observed in the wide sheet material. In support of this is cited the removal of the high values of magnetostriction in the center section when reannealed in the narrow (3 cm. vs. 75-100 cm.) widths. Also, it should be noted that the part of a sheet that approaches the results of reannealing in narrow widths is the edge portion which has most of the characteristics of the narrow material. It also should be noted that if all material could be made to have the magnetostriction characteristics of edge material, the $\pm 185 \times 10^{-8}$ specification would be met.

The next step in the development of a satisfactory material from a magnetostriction standpoint indicated a process in which the steel would undergo a heating and cooling cycle which would minimize the edge to center temperature gradients and at the same time allow a maximum elastic strain to be developed between the surface film and body of the material. These conditions seemed most likely to be met by annealing the material in a continuous open-annealing furnace.

Preliminary investigations on Epstein strips and "half sheet widths" samples indicated the possibility of lowering magnetostriction by reannealing in a hydrogen atmosphere in single sheets. These investigations showed that the sample should be heated to 1450°-1550° F. for at least five minutes in hydrogen and then cooled fairly rapidly.

After making the preliminary tests, the next step was to run a pilot experiment on the commercial product. Sheets were chosen from eleven different lots of commercial material of the best grade. A 45-inch center section of each sheet was sheared out for a control sample. The sections adjacent to the control blanks were sheared to a 45-inch length and then welded into coils. Thus, each coil contained one blank from a given lot. These are lettered A through L, respectively. Onto each end of the coils a mild steel "leader" was welded to enable the furnace to be threaded without affecting the samples. The furnace was electrically heated by elements located on the side. The heating chamber is approximately 5' x 4' x 8', and is made of brick supported in a steel shell. It was equipped with automatic controls. The strip was introduced into the front and pulled out through a slit in the back wall by hand. Hydrogen gas was introduced into the furnace chamber above and below the strip. The rate of inflow was 200 cubic feet per hour. After the hydrogen flame had burned in the furnace for an hour, one strip was fed through at the rate of one-half foot per minute. The temperature was maintained at 1500° F. After this coil was processed, the temperature was raised to 1825° F. and another coil was pulled through at the same rate. This latter coil was so badly corrugated longitudinally that it was discarded. The coil processed at 1500° was in a fair condition after treatment. The material was fairly flat. It seemed ductile and a slight oxide coloration appeared on most of the blanks. This was due to the water vapor in the furnace atmosphere. Also, it was found impossible to add hydrogen fast enough to cause it to burn at the entrance or exit of the furnace. This means that the atmosphere in the furnace was of doubtful composition at all times during the processing of the strip.

After treatment, the blanks from each lot of material were cut from the coil annealed at 1500° F. From each blank was cut an Erichsen sample of sheet width (7"), two 3 x 50 cm. Epstein samples for magnetostriction tests at 15 kilogausses induction and for microscopical examination, and a one-pound core loss sample. The core loss samples were also used for space factor determinations.

The results of these tests are recorded in the following tables. Results on commercially annealed control samples are included for comparison purposes. In the table, the "commercially annealed" samples are designated as Treatment No. 1, while the anneal in the hydrogen atmosphere at 1500° F. is Treatment No. 3.

For comparison purposes, the averages of each treatment will be considered. The "commercially annealed" averages will be considered as the standard. A betterment of an electrical steel characteristic will be designated by a plus sign, a harmful effect by a negative sign.

Comparison Table

Average % Change Due to Treatment

Property	1500° F. in Wet H_2
Core Loss - P. 10/60	+3.8
Permeability at 16 Kilogausses	-12%
Space Factor	-.4%
Ductility (Erichsen)	-2.%
Magnetostriction	+59.0%

Inspection of these results demonstrates that the treatment is effective even though the hydrogen atmosphere was of doubtful composition. After treatment, the overall average was within the range desired by

TEST RESULTS

Sample	Magnetostriction $\frac{\Delta L}{L} \times 10^{-8}$ at B=15			Core Loss Watts P 10/60/Lb. as Processed	After Aging 25 days at 212°F.	% Aged	Permeability at B=16 Kilogausses	% Space Factor	Ductility Erichsen in mm.
	Center	Edge	Average						
1-A	504	102	303	.43	.44	2.3	381	92	3.32
3-A	0	366	183	.41	.42	2.4	402	92	3.13
1-B	528	-48	288	.42	.43	2.4	314	92	2.72
3-B	120	422	271	.41	.43	4.9	334	92	2.87
1-C	488	30	259	.46	.465	.8	250	92	1.53
3-C	-48	66	57	.44	.455	3.4	238	92	2.30
1-D	720	210	465	.48	.48	0.0	340	91.5	2.50
3-D	-30	84	57	.44	.475	8.0	237	91.5	2.83
1-E	600	462	531	.455	.455	0.0	212	91.5	2.39
3-E	156	156	156	.55*	.625	13.6	220	91.5	2.06
1-F	360	0	180	.49	.51	4.1	248	91.5	3.35
3-F	48	42	45	.45	.47	4.4	251	91.5	2.85
1-G	1020	36	528	.51	.52	1.0	304	92	3.06
3-G	210	354	282	.45	.475	5.6	316	91.5	2.97
1-H	210	126	168	.44	.45	2.3	258	92	3.07
3-H	162	42	102	.42	.435	3.6	278	91.5	2.40
1-I	540	156	348	.445	.475	6.3	400	92	2.72
3-I	-78	192	135	.42	.445	5.9	372	91.5	2.48
1-J	684	30	357	.44	.44	0.0	246	92	2.77
3-J	168	60	114	.42	.44	4.8	257	91.5	3.42

TEST RESULTS (Continued)

Sample	Magnetostriction $\frac{\Delta L}{L} \times 10^{-8}$ at B=15 Center	Edge	Average	Core Loss Watts P 10/60/Lb. as Processed	After Aging 25 days at 212°F.	% Aged	Permeability at B=16 Kilogausses	% Space Factor	Ductility Erichsen in mm.
1-L	732	-36	384	.45	.45	2.2	316	92	2.43
3-L	-360	-6	183	.43	.455	5.8	300	91.5	1.98
1 - Ave.			351	.46	.47	2.2	319	91.9	2.71
3 - Ave.			143	.43	.45	4.9	282	91.5	2.66

*This sample is abnormal and so is not included in the core loss averages.

the customer; namely, 185 x $10^{-8} \frac{\Delta L}{L}$, while before it was more than double this value (351 x $10^{-18} \frac{\Delta L}{L}$). Before treatment, there were 13 out of 22 tests, or 59%, which were out of the desired range, while after treatment only six of the 22, or 27%, were unsatisfactory. Moreover, the gain in core loss is very appreciable. Of the other characteristics, only the aging is adversely affected to an appreciable extent. While the annealed material did age more than the commercial product, the aging is not sufficient to be an important factor.

While the pilot experiment was successful, it was still not satisfactory from an atmosphere standpoint. It was still desired to have a protective atmosphere of hydrogen around the sheet to maintain the benefits gained from the high temperature box anneal. As has been mentioned, the heating chamber of the furnace was so large that hydrogen gas could not be added fast enough to rid the chamber of oxygen without danger of an explosion. To correct this, a mild steel box muffle was constructed, measuring approximately 10 feet long, 28 inches wide, and 1-1/2 inches thick. The box had a 1/2 inch slit across each end (28 in. dimension). Gas connections were provided, both top and bottom, at the center of the muffle. The muffle was then inserted into the annealing furnace with 6 inches protruding from the entrance and 18 inches extending from the rear. Sufficient gas was then added to cause hydrogen gas to burn at the slits at each end of the muffle.

Three welded coils fabricated from sheets from the same lots as described in the first pilot experiment were then processed and the material given the same magnetic tests. Results are tabulated in Appendix IV. The following table gives a summary from which the conclusions may be drawn:

Coil	Temp. ° F.	Time in Furnace, Minutes	Magnetostriction $\frac{\Delta L}{L} \times 10^{-8}$ at B=15	Core Loss W/Lb. 10/60	Permeability µ at B=16
Control	--	--	344	.45	
10-3/4 Wide	1400	5	155	.449	259
27 Wide #8	1500	5	144	.418	304
27 Wide #9	1500	2	135	.419	284

The material was very flat, having a space factor of 92-93%, which is equal to the average for the commercial material of this type.

From these results, it may be concluded that an open anneal at 1500° F. for approximately five minutes will give a much improved product from a magnetostriction standpoint. Moreover, the decrease in core loss will result in a more valuable product, thus paying for the additional processing. There was some indication that a higher annealing temperature would improve the ductility of the material.

To examine the higher temperature range, three more coils were fabricated and processed in an analogous manner to the ones above. Temperatures of 1550°, 1600°, and 1650° F. were employed with a time of five minutes in the furnace. Detailed results are given in Appendix V. Nothing new was learned from these experiments, but they did confirm that open-annealing of the commercial product should produce a material that would meet the customer's specification of 185 x $10^{-8} \frac{\Delta L}{L}$ at the operating induction, provided that induction was below 15 kilogausses. This process has been reduced to commercial practice, and is producing material with the desired characteristics.

6.4 - ABRASION EXPERIMENTATION

In the search for other methods of lowering magnetostriction values, it was decided to investigate the abrasion process in more detail. When abrasion is carried out by rubbing with emery paper on a block of wood, it can be made a directional process by passing the abrasive back and forth in the same path. Because of the dimensions of the samples, 3 x 50 cm., the strokes taken with the abrasive were always parallel to the 50 cm. dimension, which is also the direction of the magnetostriction measurement, ΔL, and the direction in which the induction, B, is measured. Three of these quantities are parallel by reason of design; namely, the length of the sample, the change in length measurement, ΔL, and the induction, B. It seemed reasonable to expect that if the direction of abrasion was to have an appreciable effect, it would be observed at a maximum extent when carried out at right angles to the induction, B, and the extension, ΔL. To test this idea quickly, the magnetostriction was measured on four samples, two from the edge of commercially processed sheets, and two from the center of the same sheets. This was done to make certain that there was a range of values in the original samples. One pair of samples, center and edge, was abraded parallel to the 50 cm. dimension, while the other two were abraded perpendicular to this direction. All samples were then re-tested. Results follow:

Sample No.	Direction of Abrasion Relative to Flux (50 cm)	Wt. of Matl. Removed during Abrasion. Orig. Wts. about 29 Grams	Magnetostriction at B=15 Kilogausses ($\frac{\Delta L}{L}$) Before Abrasion	After Abrasion
M-3 Edge	Perpendicular	.44 grams	$+72 \times 10^{-8}$	-30×10^{-8}
M-3 Center	Perpendicular	.36	+198	-36
V-3 Edge	Parallel	.52	+48	+480
V-3 Center	Parallel	.32	+192	+534

These values demonstrate that:

1. Light abrasion parallel to the flux direction increases magnetostriction.

2. Light abrasion perpendicular to the flux direction decreases magnetostriction.

To examine the relationship further, it was decided to examine orientations between the two extremes. Five adjacent test strips were cut parallel to the rolling direction from the center of a commercially processed sheet. Five more strips were cut from the same sheet perpendicular to the rolling direction. The magnetostriction was then measured on several of the pieces to determine the magnetostriction of the material as received. Two pieces (one parallel and one transverse to the rolling direction) were then abraded in the 0°, 30°, 45°, 60°, 90° direction relative to the 50 cm. dimension.

Rolling* Direction	Abrasion Direction*	Weight Loss During Abrasion	Magnetostriction ($\Delta L/L$ at B=15) Before Abrasion	After Abrasion	Change
Parallel	0°	.50	318×10^{-8}	420×10^{-8}	$+102 \times 10^{-8}$
"	30	.42	342	372	+32
"	45	.75	330	330	0
"	60	.40	330 (Estimated)	270	-60
"	90	.40	330 (Estimated)	180	-150
Transverse	0°	.52	219 (Estimated)	324	+105
"	30		216	Bent during abrasion.	
"	45	.86	222	284	+62
"	60			Bent during abrasion.	
"	90	.48	219 (Estimated)	156	-63

*Directions measured relative to the 50 cm. dimension of the Epstein strip.

The conclusions to be drawn are:

1 - The effect on magnetostriction by surface abrasion is dependent upon the relation between the direction of abrasion and the direction of magnetic flux.

2 - When the direction of abrasion is parallel to the induction, B, the change in magnetostriction is at a positive maximum.

3 - When the abrasion is perpendicular to the induction, the change in magnetostriction is at a negative maximum.

4 - The effect is a minimum when the abrasion is at 45° to the induction.

Following these experiments, the same ideas were carried out on full-sized sheets using floor sanders and sand blast to accomplish the abrasion with essentially the same result. A patent application was filed and the patent issued covering the use of abrasion for the control of magnetostriction. The patent number is U. S. 2,234,968 (Appendix VI). The great difficulty in the use of this method commercially is the inability of controlling the abrasion process so as to do a minimum amount of harm to the permeability and core loss through the introduction of non-elastic stresses. The space factor also is adversely affected, for the material must be coated to reëstablish the interlamination resistivity.

7.0 - SUMMARY

The results of the work presented in this dissertation are as follows:

1. The application of Wheddington's ultra-micrometer to the measurement of the Joule magnetostrictive effect in Epstein samples of silicon-iron.

2. Investigation of the variables affecting magnetostriction in silicon-iron sheets.

3. Development of methods of processing suitable for the control of the Joule magnetostrictive effect.

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A C K N O W L E D G M E N T

Appreciation is expressed for the grant of the cooperative fellowship made possible by the joint contributions of The American Rolling Mill Company (ARMCO) and the University of Cincinnati. It is desired particularly to express thanks for the opportunity of presenting the thesis after the elapse of some five years which were occupied by service in World War II.

The subject of the thesis was suggested by Dr. Anson Hayes, Director of the ARMCO Research Laboratories. His suggestions and discussions of the problem were timely, interesting, and a source of encouragement.

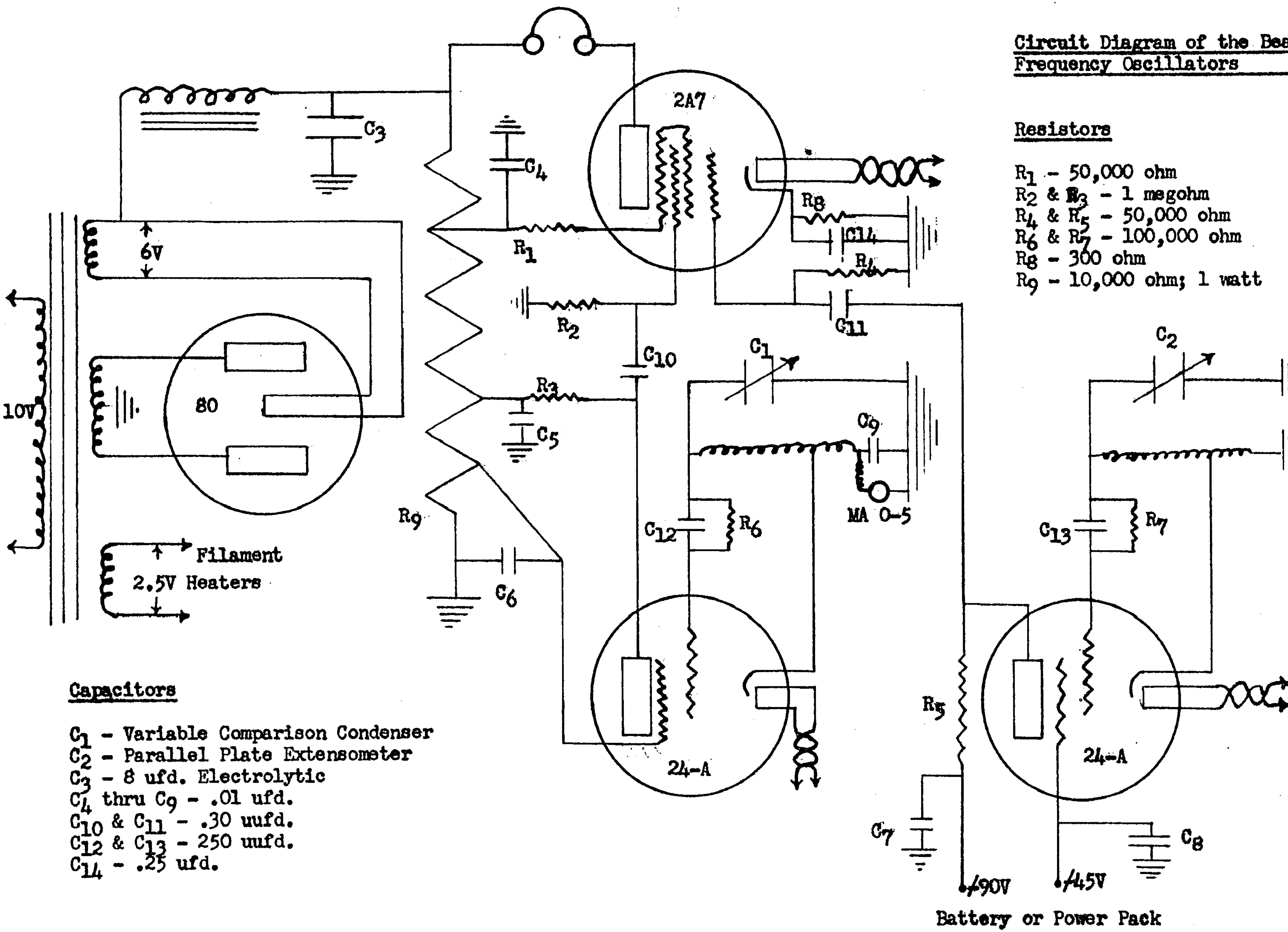
The Electrical Steel research group of ARMCO, headed by Mr. G. H. Cole, was exceedingly helpful and cooperative in all phases of the work. Particular mention should be made of Don S. Wolford and V. W. Carpenter, the former in relation to methods of testing magnetic materials, and the latter for his thorough knowledge of processing.

Mr. J. C. Young, Supervisor of Apparatus Design and Construction at ARMCO, and his technicians, made possible the construction of much of the equipment used in connection with this work.

Many others contributed to the success of this project, and their efforts are greatly appreciated, even though space does not permit their being specifically mentioned.

Dan M. Hayes

Circuit Diagram of the Beat Frequency Oscillators



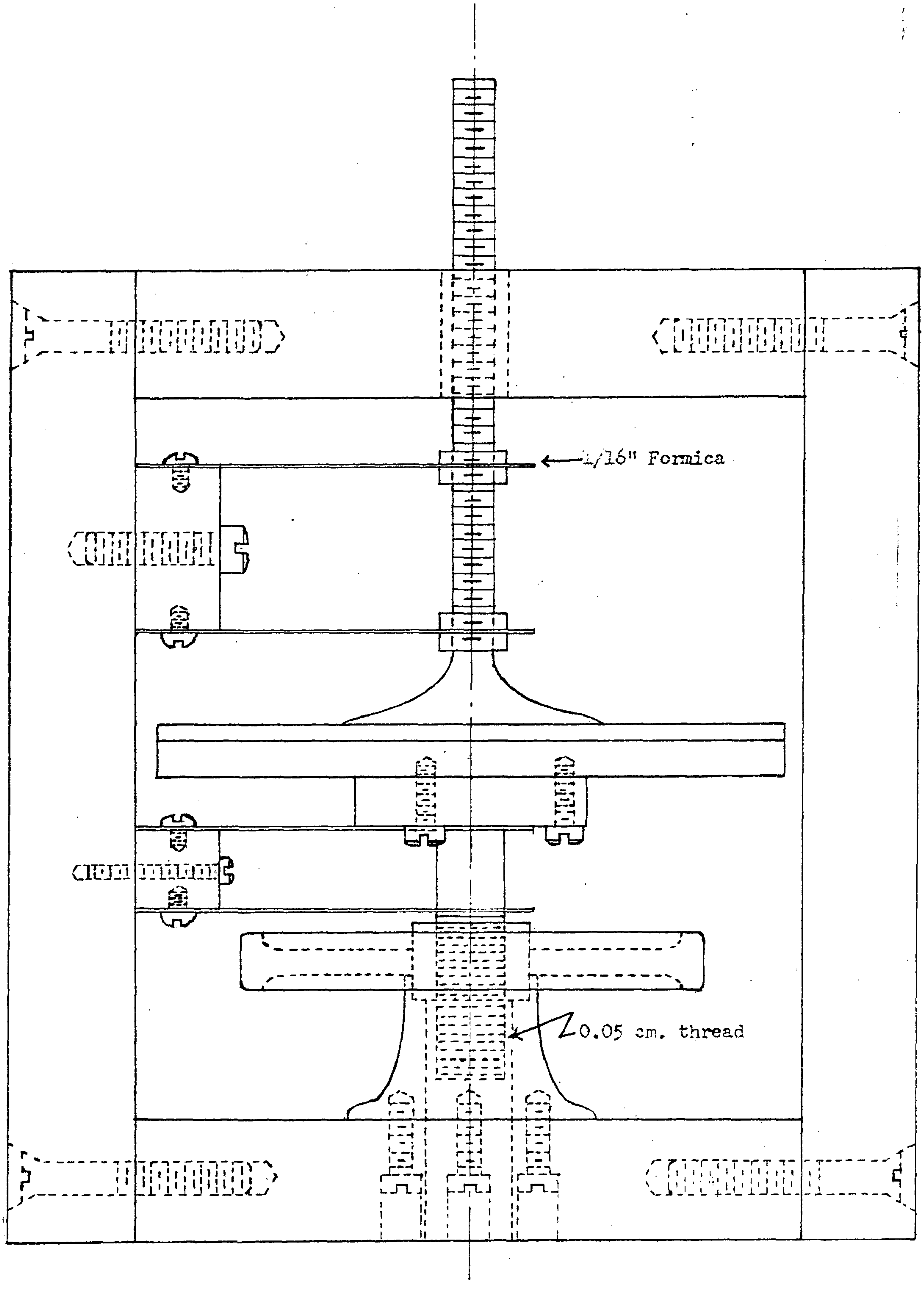
Resistors

R_1 - 50,000 ohm
R_2 & R_3 - 1 megohm
R_4 & R_5 - 50,000 ohm
R_6 & R_7 - 100,000 ohm
R_8 - 300 ohm
R_9 - 10,000 ohm; 1 watt

Capacitors

C_1 - Variable Comparison Condenser
C_2 - Parallel Plate Extensometer
C_3 - 8 ufd. Electrolytic
C_4 thru C_9 - .01 ufd.
C_{10} & C_{11} - .30 uufd.
C_{12} & C_{13} - 250 uufd.
C_{14} - .25 ufd.

APPENDIX I

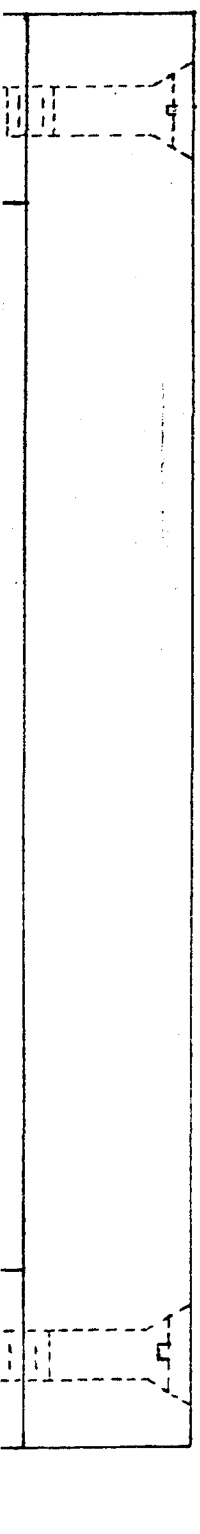

1/16" Formica
0.05 cm. thread

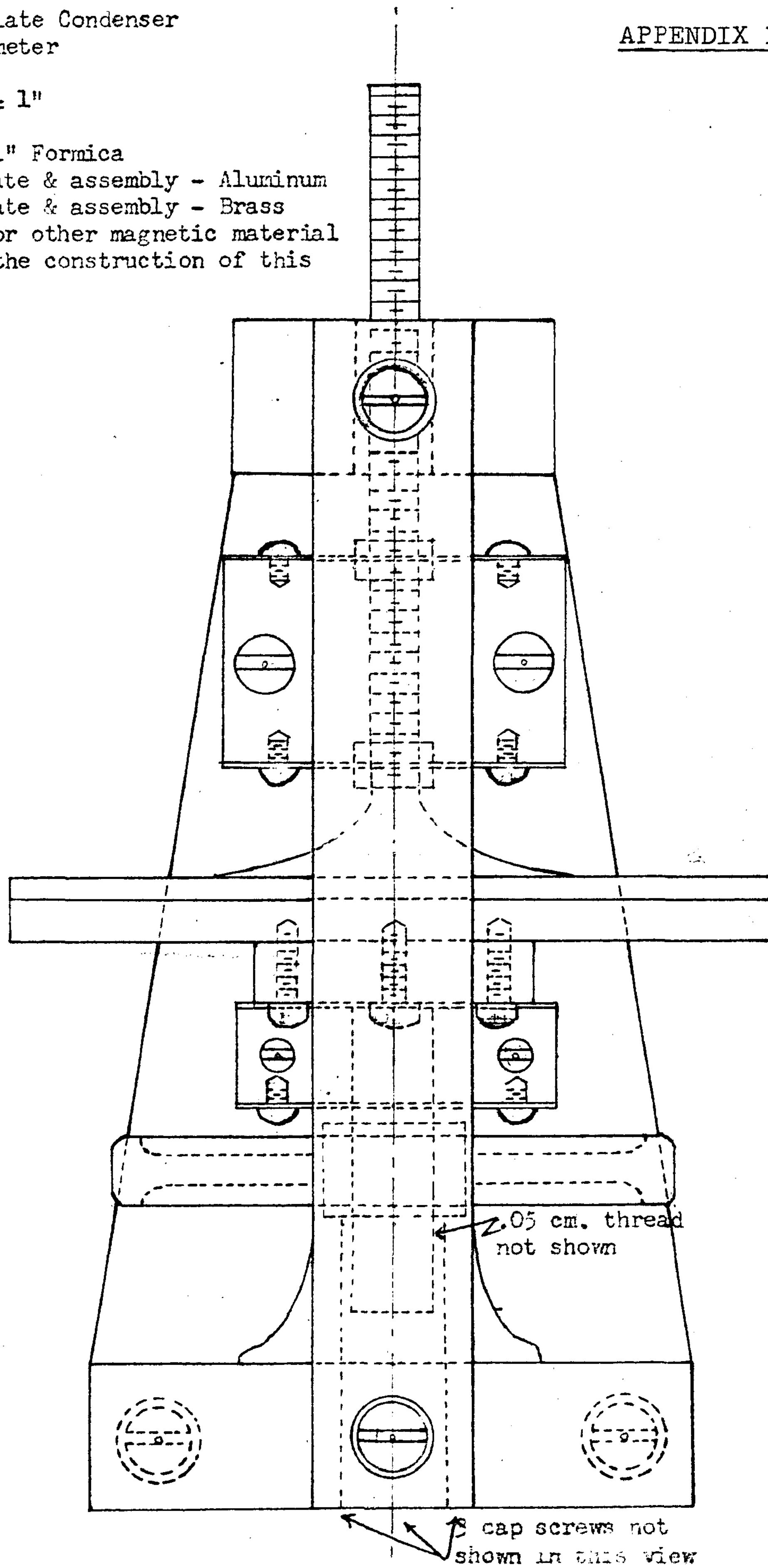
APPENDIX II

APPENDIX II

Parallel Plate Condenser
or Extensometer

Scale 1" = 1"
Materials:
 Frame - 1" Formica
 Upper plate & assembly - Aluminum
 Lower plate & assembly - Brass
 No iron or other magnetic material
 used in the construction of this
 item.





CALIBRATION CALCULATIONS

A. Displacement through known Distance

$$280 \text{ Divisions} = .833 \times 10^{-3} \text{ cm.}$$

$$1 \text{ Division} = \frac{.833}{280} \times 10^{-3} \text{ cm.}$$

$$= 2.97 \times 10^{-6} \text{ cm.}$$

With measurements on 50 cm. samples

$$\frac{\Delta L}{L} = \frac{2.97 \times 10^{-6}}{50} = 5.96 \times 10^{-8}$$

B. Capacitance Measurement

$$C = \frac{.0885\ AK}{S}$$

$$\frac{dC}{dS} = \frac{-.0885\ AK}{S^2}$$

$$C = 600\ \mu\mu f \qquad A = 6^2\pi = 113.1 \text{ cm.}^2 \qquad K \doteq 1$$

$$S = \frac{.0885 \times 113.1}{600} = 1.67 \times 10^{-2} \text{ cm.}$$

Then

$$\frac{dC}{dS} = \frac{.0885 \times 113.1}{(1.67 \times 10^{-2})^2} = 3.58 \times 10^4$$

For $\Delta S \ll S$

$$\Delta C = 3.58 \times 10^4\ \Delta S$$

$$\Delta C \times 2.82 \times 10^{-5} = \Delta S$$

or now

$$\Delta C = 1 \text{ Dial Division} = .106\ \mu\mu f \quad \therefore \quad \Delta S = 3.02 \times 10^{-6}$$

$$\frac{\Delta L}{L} = \frac{3.02 \times 10^{-6}}{50} = 6.04 \times 10^{-8} \text{ cm.}$$

APPENDIX IV

TABLE I

MATERIAL USED FOR OPEN ANNEALING EXPERIMENTS

Code	Heat No.	Lot No.	Box No.	Stock Card No.	Ladle Silicon	Production Control Tests W/Lb.	Production Control Tests Erichsen
A	9315-O	52014	73061	920145-B	4.79	.48	2.8
B	9275-W	51818	72823	919063-C	4.80	.495	3.2
C	9315-T	52124	73139	920187	4.79	.485	3.2
D	9287-T	52111	73115	919675-B	4.81	.48	3.1
E	9348-V	52207	73071	920167	St.Gr.	.42	Sheet Test
F	B-9355-P	52055	73084	919893	4.83	.48	2.8
G	9317-P	51893	72894	42017	4.78	.52	3.9
H	9287-S	52028	73071	919954-C	4.81	.48	2.8
I	9287-P	52010	73060	919952	4.81	.495	2.8
J	9291-Y	52104	73107	919390	4.75	.47	3.1
L	9287-Y	52143	73154	920158-C	4.81	.47	2.7

TABLE II - AVERAGE ERICHSEN VALUES OF THE MATERIAL AS MILL ANNEALED AND OPEN ANNEALED IN THE LABORATORY

Code	As Mill Annealed		10-3/4" Wide Coil OA at 1400°F. 1 Ft./Min.		27" Wide Coil OA at 2-1/2'/Min. at 1500°F.		27" Wide Coil OA at 1500°F. at 1 Ft./Min.	
	Erichsen in mm.	% of Draws under 2 mm.	Erichsen in mm.	% of Draws under 2 mm.	Erichsen in mm.	% of Draws under 2 mm.	Erichsen in mm.	% of Draws under 2 mm.
A	3.32	20	2.46	20	2.72	0	3.35	0
B	2.72	30	1.46	100	1.98	50	2.65	10
C	1.53	100	1.84	80	1.86	70	2.12	40
D	2.50	10	1.60	100	1.73	90	1.66	70
E	2.39	30	1.56	100	1.61	100	1.46	100
F	3.35	10	2.52	20	1.88	80	2.04	30
G	3.06	10	3.18	20	2.98	10	3.16	0
H	3.07	0	2.32	20	2.84	0	3.19	0
I	2.72	0	1.90	60	3.23	0	2.31	50
J	2.77	40	3.04	20	3.41	0	3.46	0
L	2.43	10	3.20	0	2.07	40	1.84	60
Avg.	2.71	24	2.28	49	2.39	40	2.48	33

Footnote: One ft./min. equivalent to 5 min. in heating chamber.

TABLE III - RESULTS OF MAGNETIC TESTS OF OPEN ANNEALED COILS*

Code	Commercial Test Lot	10-3/4" Coil OA at 1400°F. at 1'/Min.		Blank #7 Mill Annealed			Coil #8 Open Ann. at 1500°F. at 2-1/2'/Min.				Coil #9 Open Ann. at 1500°F. at 1'/min.			Blank #10 as Mill Ann.
	W/Lb. 10/60 50-50	W/Lb. 10/60 St.Gr.	B=16 St.Gr. μ	W/Lb. St.Gr.	10/60 50-50	% Grain Factor	W/Lb. St.Gr.	10/60 50-50	% Grain Factor	B=16 St.Gr. μ	W/Lb. St.Gr.	10/60 50-50	B=16 St.Gr. μ	W/Lb. 10/60 St.Gr.
A	.48	.465	224				.422			359	.40	.51	371	.43
B	.495	.473	240	.43	.51	16	.40	.495	19	397	.395		332	.42
C	.485	.435	263				.435			229	.42		251	.46
D	.48	.450	297				.435			229	.435		222	.48
E	.42 St.	.437	240				.39			381	.435		219	.48
F	.48	.440	265	.466	.48	2	.44	.44	0	248	.43	.46	224	.49
G	.52	.475	272	.505	.51	1	.445	.49	9	306	.445	.475	309	.515
H	.48	.440	287				.420			261	.41		248	.44
I	.495	.470	224				.415			276	.40		402	.445
J	.47	.440	232	.42	.485	9	.405	.46	12	322	.395	.445	246	.440
L	.47	.412	313	.43	.46	6	.39	.445	12	335	.38	.445	305	.450
Avg.	.485	.449	259	.45	.489	7	.418	.466	10	304	.414	.467	284	.46

Avg. of Grain Factor Samples .416

*All magnetic tests on as-cut samples.

TABLE IV - RESULTS OF MAGNETOSTRICTION TESTS ON OPEN ANNEALED COILS*

Sample	Position	Mill Annealed	10-3/4" Coil OA at 1400°F. at 1'/Min.	Coil #8 OA at 1500°F. at 2-1/2'/Min.	Coil #9 OA at 1500°F. at 1'/Min.
A	Edge	102	0	-30	-24
	Center	504	246	162	150
	Avg.	303	123	96	87*
B	Edge	-48	-12	-72	-36
	Center	528	342	222	72
	Avg.	288	177	147	54
C	Edge	30	102	120	-30
	Center	488	342	102	186
	Avg.	259	222	111	108
D	Edge	210	-12	78	36
	Center	720	306	264	234
	Avg.	465	159	172	135
E	Edge	462	42	12	156
	Center	600	300	330	228
	Avg.	531	171	171	197
F	Edge	0	42	108	120
	Center	360	186	306	246
	Avg.	180	114	207	183
G	Edge	36	42	102	126
	Center	1020	276	336	408
	Avg.	528	159	219	267
H	Edge	126	0	-48	-258
	Center	210	210	174	78
	Avg.	168	105	111	168

Table IV - Continued

Sample	Position	Mill Annealed	10-3/4" Coil OA at 1400°F. at 1'/Min.	Coil #8 OA at 1500°F. at 2-1/2'/Min.	Coil #9 OA at 1500°F. at 1'/Min.
I	Edge	156	54	0	6
	Center	540	336	156	138
	Avg.	348	195	78	72
J	Edge	30	54	-36	42
	Center	628	186	264	90
	Avg.	857	120	150	66
L	Edge	-36	-78	-36	-78
	Center	732	240	222	216
	Avg.	384	159	129	147
Avg. for Treatment	Edge	112	40	58	83
	Center	575	270	231	186
Grand Avg. for Treatment		344	155	144	135

*All tests run at 15 kilogauss induction under a load of 1040 grams.

August 1, 1938

From: Dan M. Hayes

To: G. H. Cole, Associate Director, Research

Subject: LOW TEMPERATURE OPEN ANNEALING OF #000 AW COILS.

S.I. 38-264 (Magnetostriction Supplement)

In my letter of June 10, 1938 (S.I. 38-201 - Magnetostriction Supplement) it was pointed out that there was some indication that a higher temperature than 1500° F. might be advantageous for lowering magnetostriction and core loss. Since that date, three test coils of material have been processed for five minutes at 1550° F., 1600° F., and 1650° F., respectively, in a hydrogen atmosphere.

Each coil contained blanks from ten different lots of material. Magnetostriction samples were cut from the edge and center of each blank and tested at 12.5 and 15 kilogausses. For each test on a treated material there was a corresponding test on an "as mill annealed" control sample from the same sheet. The results of these tests are reported in the appended table.

My analysis of these data is as follows: There is little or no difference in the magnetostriction characteristics of the coils annealed at the three temperatures. This statement is based on the averages of the tests on center strips. These figures are:

Test at B=12.5

Coil #4	Annealed at 1550° F. Ave.	$-81 \times 10^{-8} \frac{\Delta L}{L}$
Control		$-188 \times 10^{-8} \frac{\Delta L}{L}$
Coil #3	Annealed at 1600° F. Ave.	$-88 \times 10^{-8} \frac{\Delta L}{L}$
Control		$-175 \times 10^{-8} \frac{\Delta L}{L}$
Coil #1	Annealed at 1650° F. Ave.	$-88 \times 10^{-8} \frac{\Delta L}{L}$
Control		$-175 \times 10^{-8} \frac{\Delta L}{L}$

Mr. G. H. Cole -2- August 1, 1938

Test at B=15.0

Coil #4	Annealed at 1550° F. Ave.	= 181
Control		= 305
Coil #3	Annealed at 1600° F. Ave.	= 155
Control		= 298
Coil #1	Annealed at 1650° F. Ave.	= 179
Control		= 298

From the standpoint of magnetostriction, one annealing temperature has little or no advantage over any other with the limitation that the temperature be above 1500° F.

The experiments allow the conclusion that if magnetostriction values are in the neighborhood of 100 to 400 x $10^{-8} \frac{\Delta L}{L}$ they may be reduced by open annealing in hydrogen to 100 or below when measured at 12.5 kilogausses.

Dan M. Hayes

cc: W. J. Beck
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File

MAGNETOSTRICTION TEST DATA

1-Edge Sample
12-Center Sample

Magnetostriction ($\frac{\Delta L}{L}$ x 10^{-8})

Sample	Tested at B=15 Annealed at 1500°F.	Tested at B=15 Control	Tested at B=12.5 Annealed at 1500°F.	Tested at B=12.5 Control
M - 4 - 1	54	198	00	90
12	240	240	120	150
N - 4 - 1	78	168	36	108
12	186	174	90	78
O - 4 - 1	-162	162	-96	90
12	174	78	72	12
P - 4 - 1	54	-90	6	--
12	216	318	84	234
R - 4 - 1	-120	180	-114	-96
12	204	486	84	264
S - 4- 1	66	156	6	72
12	176	408	90	258
T - 4 - 1	132	12	72	-42
12	222	450	126	330
U - 4 - 1	-12	198	-24	108
12	234	228	84	156
V - 4 - 1	162	204	-96	102
12	-24	300	-6	156
W - 4 - 1	-360	276	276	168
12	138	288	288	162

MAGNETOSTRICTION TEST DATA

1 - Edge Sample
12 - Center Sample

Magnetostriction ($\frac{\Delta L}{L}$ x 10^{-8})

Sample	Tested at B=15 Annealed at 1600° F.	Tested at B=15 Control	Tested at B=12.5 Annealed at 1600° F.	Tested at B=12.5 Control
M - 3 - 1	72	198	30	90
12	198	240	102	150
N - 3 - 1	120	168	30	108
12	186	174	126	78
O - 3 - 1	60	162	6	90
12	24	78	12	12
P - 3 - 1	24	-90	-24	--
12	168	318	96	234
R - 3 - 1	18	180	00	96
12	76	486	24	264
S - 3 - 1	114	156	42	72
12	228	408	136	258
T - 3 - 1	---	12	---	-48
12	---	450	---	330
U - 3 - 1	-18	198	-24	108
12	186	228	120	156
V - 3 - 1	48	204	12	102
12	192	300	114	156
W - 3 - 1	12	276	-18	168
12	138	288	60	162

MAGNETOSTRICTION TEST DATA

1 - Edge Sample
12 - Center Sample

Magnetostriction ($\frac{\Delta L}{L}$ x 10^{-8})

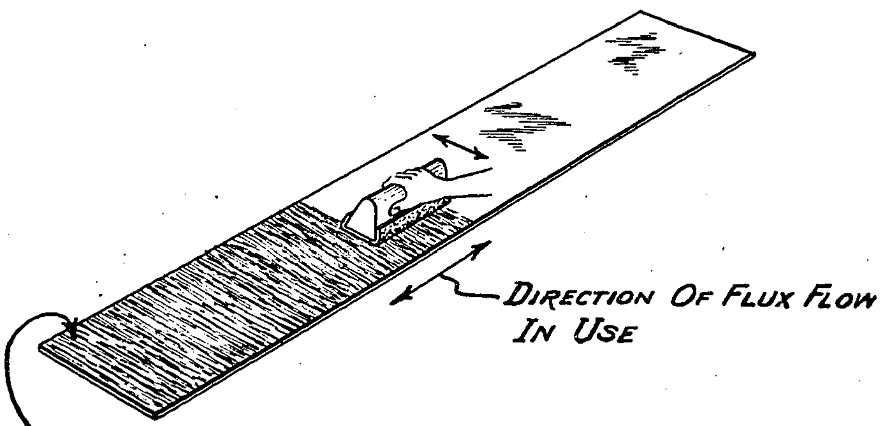
Sample	Tested at B=15 Annealed at 1650° F.	Tested at B=15 Control	Tested at B=12.5 Annealed at 1650° F.	Tested at B=12.5 Control
M - 1 - 1	48	198	00	90
12	192	240	78	150
N - 1 - 1	126	168	36	108
12	228	174	96	78
O - 1 - 1	46	162	00	90
12	180	78	96	12
P - 1 - 1	60	-90	24	--
12	168	318	90	234
R - 1 - 1	96	180	30	96
12	150	486	66	264
S - 1 - 1	72	156	48	72
12	150	408	72	258
T - 1 - 1	174	12	90	-42
12	312	450	144	330
U - 1 - 1	72	198	24	108
12	138	228	54	156
V - 1 - 1	36	204	-6	102
12	210	300	108	156
W - 1 - 1	36	276	-12	168
12	162	288	84	162

APPENDIX VI

March 18, 1941. D. M. HAYES ET AL 2,234,968

ART OF REDUCING MAGNETOSTRICTIVE EFFECTS IN MAGNETIC MATERIALS

Filed Nov. 12, 1938



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Patented Mar. 18, 1941 2,234,968

UNITED STATES PATENT OFFICE

2,234,968

ART OF REDUCING MAGNETOSTRICTIVE EFFECTS IN MAGNETIC MATERIALS

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Application November 12, 1938, Serial No. 240,202

14 Claims. (Cl. 175—356)

The phenomenon of magnetostriction, which is the property possessed by many magnetic materials of undergoing a dimensional change or distortion when magnetized and de-magnetized is well known. It becomes a significant factor in the construction particularly of electrical power transformers, since the magnetostriction of the core is an important source of the noise emanating from these transformers when in operation. The noise becomes so great in some instances as to constitute a public nuisance. As a consequence, it is desired to provide magnetic materials for this and for analogous uses, in which materials the magnetostrictive effect is at a minimum. It has come to be the practice to purchase magnetic materials to be used for such purposes on specifications, one feature of which is a maximum permissible magnetostrictive effect. Different magnetic materials have different magnetostrictive characters; but it will frequently be found that different portions of the same batch of sheets exhibit different magnetostrictive effects. The cause of this variation in magnetostriction is not fully understood. A great deal of work has been done on various ways of minimizing magnetostriction, but so far as we know, without significant result.

The improvements in the magnetic properties of core loss and permeability, which have been made from time to time have made possible considerable economies in transformer design which involve the operation of the transformers at higher and higher induction. The magnitude of the magnetostrictive effect, however, increases with the induction, and further progress in this direction is blocked by its rising to a point where the transformers become objectionably noisy. In many cases it is necessary, because of this effect, to design transformers to operate at lower inductions than the induction at which they should operate to take full advantage of the otherwise excellent magnetic properties of the core material. This lowered induction makes it necessary to use more material in the core, which increases its cost and size. Removal of this magnetostriction limitation is obviously desirable, not only to reduce the noise from transformers of present design, but to permit the complete utilization of the properties of present and future core material.

Various tests for magnetostriction and for the effect of magnetostriction in transformer operation have been worked out, but it is not felt that these need be described here.

The noise level in a transformer is usually measured in decibel units. The unit is defined by the following relation:

$$db.=10\log_{10}\frac{(P_1)}{(P_2)} \qquad (1)$$

P_1=Power in the sound wave being measured
P_2=Power in a standard comparison wave of low intensity

The power in a sound wave is proportional to the square of the amplitude (a) of the wave.

$$P=K^1(a)^2 \qquad (2)$$

If in addition it be assumed that the amplitude of the sound wave is proportional to the magnetostriction ($\Delta L/L$) one obtains for the power

$$P=K^1(a)^2=(K^1(K'')^2\times(\Delta L/L)^2) \qquad (3)$$

Where $\Delta L/L$ represents the ratio of the change in length to the original length, i. e., the magnetostriction. Substituting back in Equation (1) one can obtain

$$db.=20\log_{10}\frac{(\Delta L/L)_1}{(\Delta L/L)_2}$$

By measuring the noise level of a transformer, and the magnetostriction of the steel in that transformer, application of the above relation will give the noise level of the transformer for all possible magnetostriction values.

On one batch of transformers recently tested for magnetostriction and noise level, the magnetostrictive effect was found to have a value of 500×10^{-8} which was representative of a noise level value of 90 decibels. Such a transformer therefore produced a noise level equivalent to that of the average motor truck at a distance of fifteen to twenty feet.

The object of our invention is the provision of a means of treating electrical steels to diminish their magnetostrictive effect, and the production of a new material as so treated. It is an object of our invention to provide a method of treating magnetic material which does not add greatly to the cost of it and which may be practiced upon the material either in the form of sheets or strips or in the form of completed transformer punchings. It is an object of our invention to provide a treatment which not only may be applied to material in the course of manufacture so as to deliver a finished product having a minimum of magnetostriction for the particular analysis involved, but also which may be applied to a series of stampings found by test to have too high a magnetostrictive effect so as to salvage such materials when otherwise they would have to be discarded.

These and other objects of our invention which will be understood by the skilled worker in the art more fully upon reading these specifications, we accomplish by that certain procedure and in that certain novel product of which we shall now describe an exemplary embodiment.

This embodiment has to do with silicon steels, and it may be stated at the outset that it is effective to reduce the magnetostrictive characteristics of silicon steels of all analyses, including both alloys of which the principal ingredients are iron and silicon, and also alloys containing other materials, in addition to iron and silicon, such for example, as manganese or other alloying elements. But the invention herein involved is not limited to alloys classifiable as silicon steels, and is applicable to the general range of magnetic alloys of all types and will produce in them significant diminutions in magnetostriction. It will be understood that as the normal magnetostrictive effects of alloys will vary with their formulae, so also the procedure and treatment herein set forth will effect different diminutions in magnetostriction in different alloys, depending upon their formulae.

The basis of the invention here involved is the discovery of the peculiar action of sheets or laminae of magnetic alloys when their surfaces are abraded. Considering first transformer laminations in the form of elongated strips which are to be so located in a transformer coil that the lines of magnetic flux will pass through the laminae from one end to the other in a direction parallel to their longer or major axes, certain effects can be produced. Others have observed that if the surfaces of the laminae are slightly abraded in the direction of the major axis the magnetostrictive effect exhibited by the laminae will be substantially increased. We have found that if the abrading is done in a direction substantially at an angle of 45° to the major axis of the strip, there will be little or no effect on its magnetostriction. We have made the important discovery, however, that if the abrading is done transversely to the major axis of the strip, i. e. across the strip and perpendicularly to the direction of flow of the magnetic lines of force therein, a notable decrease in the magnetostrictive effect will be observed upon the test.

The particular reasons why this is so are not completely understood. It is supposed that the magnetostrictive effect is one involving a surface condition so that if the surface is broken up in a direction transverse to the direction of primary distortion due to the magnetostrictive effect, the resultant distortion will be considerably diminished.

In the drawing we have shown diagrammatically the action of abrading the surface of a lamina in a direction normal to a predetermined direction of flux flow therein as said lamina is to be used.

The abrasion may be carried on in a number of different ways. It may be accomplished by hand by fastening a sheet of suitable abrading material such as emery cloth to a block of wood, positioning the laminae upon a table or other support and rubbing their major surfaces with the abrader block in a direction across the proposed lines of magnetic force, and perpendicular to these proposed lines for the greatest effect, as has been set forth; or a stone or other abrasive block may be employed. Likewise a grinding wheel may be set up so as to traverse the work in the proper direction, the direction of the rotation of the grinding wheel also being such as to abrade the work in the proper direction.

Sand blasting likewise will serve and is in general a relatively inexpensive and convenient way of carrying on the invention. In using the sand blast, having ascertained the direction in which the magnetic lines of force are to flow in the work under treatment, we direct the sand blast nozzle or nozzles onto the work at an angle (for example 30 to 45°) to the plane of its surface, the nozzle being directed across the work in a direction perpendicular to the proposed direction of the lines of force. To make this clearer, if the work occupies a horizontal plane, the axis of the nozzle will lie in a vertical plane erected perpendicular to a line representing the proposed direction of the lines of force in the work, and the nozzle will be directed toward the work at an angle, for example of 30 to 45°. More than one nozzle may be employed simultaneously, of course; and it is possible to treat the whole surface of a large sheet, or a large section of a strip of magnetic material at one time.

Transformer stampings are preferably made in such a way that the lines of magnetic force passing through them (when they are assembled in the form of a core) will coincide with the direction in which the magnetic material has been rolled. This is especially advantageous with some of the more modern magnetic materials which exhibit a much greater permeability in the direction of rolling than in other directions. It will be obvious that if the manner in which the transformer stampings are to be cut from sheets or strip is known, the sheets or strip can be given our treatment prior to the formation of the laminae or stampings. Thus if straight transformer legs are to be cut from sheet or strip, it will be usual to treat the sheet or strip after manufacture but before the formation of the stampings by abrading it in a direction perpendicular to its major axis. But the laminations themselves may be treated after fabrication, and it will be clear that where L-shaped, C-shaped, or E-shaped transformer stampings are being made it will be within the scope of our invention to abrade the body portion of these shapes in one direction and the leg portion or portions in another direction or directions, depending upon the path of the magnetic lines of force passing through them after the assembly of the transformer. Thus the two legs of an L-shaped lamination may be abraded in directions perpendicular to the axes of these legs, although this involves abrading one leg in a direction at right angles to the treatment of the other leg.

Moreover, magnetic materials may be abraded at any stage in their manufacture which is not followed by some other stage effective to destroy the abraded surface. For example, sheets or strips of magnetic materials may be given the abrasion treatment by the steel manufacturer before the sheets or strips are sold to the transformer manufacturer; and the transformer manufacturer may then cut up the material as by slitting, shearing or stamping, and anneal and/or insulate the laminae so formed without destroying the effect of the abrasion, providing the surfaces of the laminae are not so corroded or oxidized during annealing as to form a new and non-abraded surface. An amount of rolling or working treatment sufficient to produce a new surface on the material, will destroy the effect of previous abrasion, as will be readily understood. Where it is necessary to follow such practices or their equivalent, it will become necessary to re-abrade the pieces.

The abrasion need not remove any material quantity of the body metal. It seems unnecessary to point out that where we speak of abrasion we mean an abrasion of the surface of the body metal. If the material is covered with a layer of scale or other substance it is not effective merely to abrade the surface of such layer. By way of illustration of the effect of the procedure herein outlined, we append a table showing the result of abrasion in different directions of four straight grain strips of silicon steel fifty centimeters long and three centimeters wide. The silicon steel was a material containing approximately 4.7 per cent silicon and .010 per cent carbon, balance substantially all iron. The abrasion was accomplished by hand with a coarse emery paper fastened to a wooden block. The strips were supported on a flat surface during abrasion and rubbed in the directions indicated in the table below.

Sample No.	Direction of abrasion relative to flux	Weight of material removed during abrasion-original weights about 39 grams	Magnetostriction at B=15 kilogausses	
			Before abrasion	After abrasion
		Grams		
M—3—E	Normal	.44	$+72\times10^{-8}$	-30×10^{-8}
M—3—C	do	.36	$+198\times10^{-8}$	$+36\times10^{-8}$
V—3—E	Parallel	.52	$+48\times10^{-8}$	$+480\times10^{-8}$
V—3—C	do	.32	$+192\times10^{-8}$	$+534\times10^{-8}$

In the course of our work we have ascertained that the effect upon magnetostriction of surface abrasion is dependent upon the relation between the direction of the abrasion and the direction of the magnetic flux. The effect is at a minimum when the abrasion direction is inclined at an angle of substantially 45° to the direction of the flux. A maximum increase in magnetostriction occurs when the direction of the abrasion coincides with the direction of the flux. A maximum decrease in magnetostriction occurs when the direction of the abrasion is directly across or at 90° to the direction of the flux. We have indicated that the amount of decrease will vary with the composition of the material. The maximum lowering of magnetostriction by abrasion which we have so far observed on any material is 220×10^{-8} at an induction of 15 kilogausses. The average decrease is approximately half that value; but with most magnetic materials it will be clear that our treatment will bring the magnetostrictive effect to values such that the averages of lots will be not greater than 100×10^{-8} at 15 kilogausses, which results in a material suitable for use in power transformers.

It will be understood that we are not restricted to any particular method of abrading the surfaces of magnetic materials since any of the usual methods of abrasion appear to serve; and when we speak of the direction of abrasion we intend to be understood as meaning the formation of abrasion scratches in the direction indicated irrespective of the particular manner in which the operation is carried on. The effect of the process appears to be dependent upon the formation of a considerable number of scratches or ridges and depressions in the surface of the metal which are longer than they are wide and which preponderantly lie in a direction transverse to the proposed direction of the lines of magnetic force in the material.

Modifications may therefore be made in our invention without departing from the spirit of it.

Having thus described our invention, what we claim as new and desire to secure by Letters Patent, is:

1. A process of treating magnetic sheet-like materials for inductive uses which comprises ascertaining the direction of flow of magnetic lines of force therein in the use indicated and abrading at least one major surface of such materials in a direction substantially normal to the said direction of flow of magnetic lines of force in said materials.

2. A process of treating magnetic sheet-like materials for inductive uses which comprises ascertaining the direction in which magnetic lines of force will flow in such materials in the use indicated, and forming in at least one major surface of such materials a plurality of indentations of greater length than width, the preponderant direction of the length of such indentations being substantially normal to the said direction of flow of said magnetic lines of force.

3. A process of treating magnetic sheet-like materials for inductive uses which comprises ascertaining the direction of flow of lines of magnetic force in said materials in said use and then breaking up at least one major surface of the said materials by scratching said surface in a direction substantially normal to said direction of flow.

4. A process of treating magnetic sheet-like materials for inductive uses which comprises ascertaining the direction of flow of lines of magnetic force in said materials in such use and scratching a major surface of said materials in a direction substantially normal to said direction of flow.

5. Magnetic sheet-like material for inductive uses comprising a body of magnetic material adapted to be located in inductive apparatus so that the lines of magnetic force will flow therein in a certain direction, a major surface of said material being scratched in a direction substantially normal to said first mentioned direction.

6. Magnetic sheet-like material for inductive uses comprising a body of magnetic alloy having a major surface broken up by relative depressions and protuberances of greater length than width and preponderantly tending in the direction of their length normal to an ascertained primary direction of flow of magnetic lines of force therein.

7. A lamination for a transformer consisting of a body of magnetic material having a major surface abraded in a direction transverse to the direction of flow of lines of magnetic force through said body.

8. A transformer lamination consisting of a body of magnetic alloy having a major surface broken up into relative ridges and depressions extending in a direction substantially normal to the direction of flow of magnetic lines of force through said body.

9. A transformer lamination consisting of a body of magnetic material having a major axis coinciding with the rolling direction of said material and the direction of its greatest permeability, said material having a major surface characterized by abrasion lines substantially normal to the direction of rolling.

10. A transformer lamination consisting of an elongated body of silicon steel having major

surfaces abraded in a direction substantially normal to the longitudinal axis of said body, the direction of rolling of said lamination and its direction of major magnetic permeability substantially coinciding with said longitudinal axis.

11. A transformer having a coil comprising a plurality of laminae assembled together, said laminae being bodies of magnetic material having major surfaces characterized by abrasion scratches extending in a direction substantially normal to the direction of flow of magnetic lines of force in said laminae.

12. A process for diminishing the magnetostrictive effect of magnetic substances which includes the steps of forming strip or sheet magnetic stock having a direction of primary magnetic permeability coinciding with the direction of rolling thereof, and abrading the major surfaces of said stock in a direction substantially normal to the direction of rolling thereof.

13. A process of producing transformer laminations which comprises forming and finishing a magnetic alloy in sheet like form, abrading a major surface of said magnetic alloy in a direction perpendicular to the direction of rolling thereof and cutting said alloy apart into transformer laminations in such a way as to cause the direction of abrasion to lie substantially normal to the path of magnetic lines of force in said laminations, without destroying the abraded character of said surface.

14. A transformer lamination consisting of a body of magnetic material having portions lying in different directions, which portions will be traversed by magnetic lines of force in directions coinciding with their longitudinal axes, each of said portions having a major surface characterized by abrasion scratches lying in a direction substantially normal to its major axis.

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