Substitution of Laminated Low-Carbon Steel for Silicon Steel in the Cores of Wire Spring Relays

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(Manuscript received May 13, 1964)

This article describes the analytical and laboratory studies undertaken to determine if low-carbon steel could be substituted for the more expensive 1 per cent silicon steel in the cores of general-purpose wire spring relays. Not only is this silicon steel more costly, but its hardness characteristics are such that tool maintenance for manufacture is an appreciable item. It was found that this substitution can be made without degrading the performance of these relays, provided the new core is made up of two laminations. When two laminations are used, the eddy current time constant of low-carbon steel matches that of the silicon steel. This is necessary to achieve the fast operate and release times now obtained and to permit satisfactory operation of present circuits when the substitution is made.

This substitution will result in substantial annual manufacturing savings for the general-purpose relays. These savings could be further increased if use of the new core could be extended to other, more special, relays of the wire spring relay family. These applications are now under study.

I. INTRODUCTION

The wire spring family of relays (see Fig. 1) was designed to serve as the basic components of modern switching circuits. It was first introduced in the No. 5 crossbar switching system and later in other systems, including a wide variety of switching applications for the Bell System. The design provides an electromagnetic device of high efficiency and reliability with excellent operating characteristics and suited to a high degree of automation in manufacture. The relays are obtainable in a wide variety of codes with different coil resistances and are capable of controlling from 1 to 24 contact sets per relay in various combinations of makes, breaks, transfers, and operating and releasing time intervals, ranging from a few milliseconds to longer than one-half second in slow-

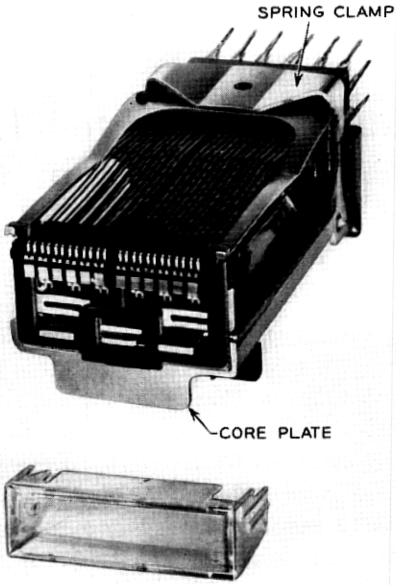

Fig. 1 — Wire spring relay.

release applications. The operating life of these relays approaches approximately one billion operations. In view of these considerations and the outstanding performance record of the relays now in use, the demand has been continually rising over the past years. Since the production of general-purpose wire spring relays began in 1950, more than one hundred million have been manufactured, and approximately twenty million of these were produced in 1963.

One per cent silicon steel was chosen originally as the magnetic core material for these relays because of its high resistivity, good magnetic properties, low aging characteristics, and its ability to achieve fast, efficient and stable operating characteristics. This material has proven satisfactory but over the years has presented some manufacturing and procurement problems. Therefore, consideration has been given to the use of alternate materials, particularly low-carbon steel for the relay cores. This article will discuss the theoretical and the manufacturing aspects involved in substituting laminated low-carbon steel for the 1 per cent silicon steel cores. Only the general run of fast-operate and fast-release relays will be considered, since the major effect of the material substitution is due to the difference in the eddy current time constants (because of the low resistivity of low-carbon steel). The slow-release relays will not be discussed, since they have built-in eddy current inducers, such as short-circuited windings or copper sleeves, which reduce the eddy current conductance of the magnet core to secondary importance.

II. PRESENT CORE DESIGN

When the general-purpose wire spring relay was developed in the late 1940's, the best material available for magnetic cores was 1 per cent silicon steel. As a result, the magnetic design of the relay was based on the use of this material. One per cent silicon steel has relatively high electrical resistivity, which keeps the eddy current time constant of the structure to a minimum, thus permitting fast operate and release times. The material has good magnetic properties with relatively high flux densities, which permit the development of ample pull forces between the relay armature and core. Also, it is a stable magnetic material that does not exhibit any significant change in properties with time. As a result, general-purpose wire spring relays with silicon steel cores have delivered reliable performance with good operating margins for the past fourteen years.

The disadvantages of silicon steel have been in the manufacturing and procurement areas. This steel is relatively difficult to fabricate by punching, because it has an abrasive action on punches and dies which necessitates frequent tool maintenance. Also, it is not as readily available and is more expensive than the low-carbon steels, such as S.A.E. 1010 steel. As a result of these considerations, there has been a continuing effort to find or adapt a substitute magnetic material for cores of general-purpose wire spring relays. This has led to the development described in the subsequent sections of this article.

III. LAMINATED CORE PROPOSAL

Recently a new and relatively inexpensive method of annealing low-carbon steel to obtain good and stable magnetic characteristics has been developed using "wet forming" gas. This annealing technique produces in low-carbon S.A.E. 1010 steel magnetic properties comparable to those obtained with 1 per cent silicon steel. Thus, low-carbon steel, which is much less expensive, could be considered as a substitute for silicon steel in the cores of general-purpose wire spring relays. However, S.A.E. 1010 steel has a nominal electrical resistivity of 12 microhm cm^{-1}, whereas the comparable value for 1 per cent silicon steel is 25 microhm cm^{-1}.

The eddy current conductance of a material is inversely proportional to the electrical resistivity; hence, the eddy current conductance of S.A.E. 1010 steel is about twice as great as that for 1 per cent silicon steel. Since the operate and release times of a relay are directly affected by the eddy current conductance, a direct substitution of S.A.E. 1010 steel for 1 per cent silicon steel would materially increase these times in general-purpose wire spring relays. Such a change in performance would be intolerable, since many switching circuits are designed to take full advantage of the fast operate and release times obtainable with the present relays. An increase in these times would result in circuit-race conditions or add to circuit holding times, thereby increasing the number of common control units needed in a central office.

Theoretically, if the volume and shape of a piece of magnetic material are not changed but the material is laminated with equal-size laminations, the effective eddy current conductance is reduced by an amount which is inversely proportional to the number of laminations. Also, if the cross-sectional area is rectangular, the eddy current conductance is further reduced as the ratio of width to thickness is increased. Thus, laminating a rectangular cross-section magnetic part reduces the effective eddy current conductance to between $1/N$ and $1/N^{\frac{3}{2}}$ of the unlaminated value, where N is the number of equal-size laminations.

Taking advantage of the recent development in annealing and the concept of laminations, it was therefore proposed that the 1 per cent silicon steel core of the general-purpose relay be replaced with a core made up of two equal laminations of S.A.E. 1010 low-carbon steel. The effect of this material change on the operation of the relay will be discussed from both the practical and theoretical aspects, with a view to showing that the change results in a relay equal in performance to those produced during the past several years, at a considerable cost saving.

IV. PRACTICAL ASPECTS OF THE PROPOSAL

In order to introduce a substitute design for a functional part of the relay, the following factors must be considered:

4.1 *Operational Factors*

(1) time characteristics
  (a) electrical operate time
  (b) electrical release time
(2) magnetic pull vs ampere turns
(3) heating (watts input vs temperature rise)

(4) life

(a) wear vs number of operations

(b) wear effect on operate and release characteristics

(5) core plate tightness (due to staking efficiency of softer 1010 steel material)

(6) corrosion protection (effectiveness of plating along laminated seam if the laminations are welded before plating).

4.2 *Manufacturing Factors*

(1) Shape of laminations

(a) economic considerations (punching properties and tool life)

(b) assembly considerations (dimensional considerations for spool-head and core plate areas)

(2) cost of material

(3) loose vs attached laminations

(a) handling ease

(b) assembly ease

(4) method of punching

(a) single (one at a time)

(b) double (two at a time, i.e., one on top of the other)

(5) welding or mating of laminations

(a) before punching

(b) after punching

(c) location of welds.

To have the laminated S.A.E. 1010 steel core accepted for use in the relay, the new design must perform as well as the old design with regard to all of the operational factors and should have definite advantages with regard to the manufacturing factors. In order to obtain the maximum improvement in the manufacturing area without affecting the over-all relay, it was necessary to introduce the minimum number of changes to the structure. As a result, the object of the laminated core proposal was to match, as nearly as possible, all of the characteristics of the present general-purpose wire spring relay having a silicon steel core with a new core of the same physical outside dimensions.

Analysis of the magnetic properties of S.A.E. 1010 steel annealed by the wet forming gas method indicated that sufficient magnetic pull would be developed with this material provided the efficiency of the relay's magnetic circuit was maintained. However, as indicated previously and analyzed in detail in the next section, laminating the core was necessary in order to reduce the eddy current conductance to tolerable levels. To be assured that the benefits of laminating the core would always be present, it was at first believed necessary to physically separate the laminations by depressions or an insulating film to prevent the flow of eddy currents between the laminations. From a manufacturing standpoint, it was decided that if this were necessary, it would be more practical to depress a large section of one of the laminations instead of using an insulating finish. As a result, the first sample cores were made this way. For comparison, a standard core is shown in Fig. 2 and laminated cores of the first design in Figs. 3 and 4.

Fig. 4, a side view of the laminations, shows the recessed section in the upper lamination to provide an air gap over the greater portion of the length of the core. The two laminations are in intimate contact at the two ends to provide a low-reluctance path for the magnetic flux to pass from the bottom lamination through the upper to the relay armature. However, timing tests of various combinations of recessed laminations, as well as flat laminations, in relays have shown that it is not necessary to create a positive or visual air gap between the parts. Apparently, the surface resistance of the laminations due to normal oxide films is sufficient to keep the eddy currents of the laminations from combining.

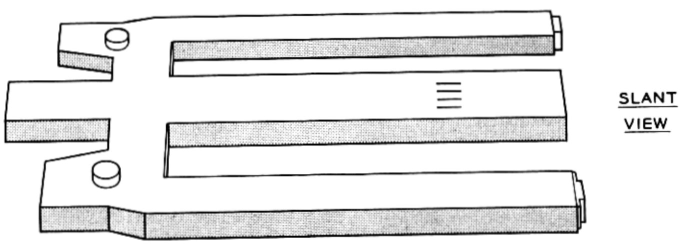

Fig. 2 — Standard one-piece core.

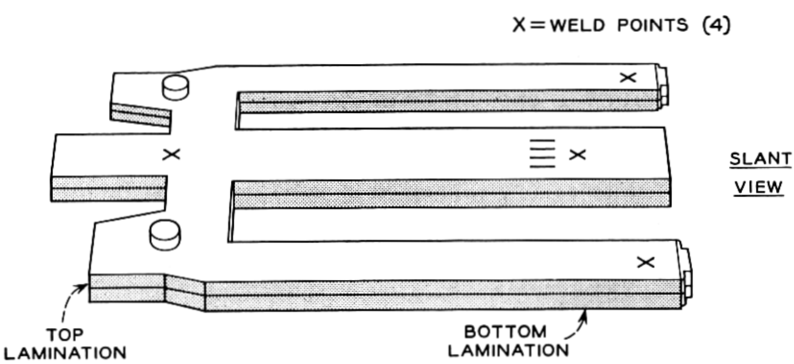

Fig. 3 — Laminated core.

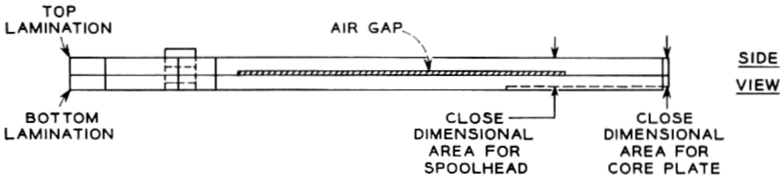

Fig. 4 — Side view of laminated core.

In Fig. 3, a slant view of the laminations, four welds are shown at points marked (X). The welding was done before magnetic annealing or plating of the parts. The welds are located at the front and rear, where they have the least effect on the eddy currents in each lamination. The welds are proposed only to associate the two laminations punched together and to facilitate the assembly of the relay. Relays were assembled and tested and satisfactory results obtained when the two laminations were not welded together. The laminations in this case were held together by the core plate at the front end and the spring clamp at the rear end after the relay had been assembled (see Fig. 1).

V. THEORETICAL ASPECTS OF THE PROPOSAL

5.1 *Symbols*

The following is a list of the symbols used in the theoretical discussions presented in the balance of this article. Where variant forms of these symbols, as distinguished by subscripts, are used in the text, they are defined in connection with the specific use.

a_1 — inner surface area of coil
a_2 — outer surface area of coil
E — applied voltage
F — magnetic pull
G — total equivalent single-turn conductance
G_c — equivalent single-turn conductance of coil — N^2/R
G_e — equivalent single-turn eddy current conductance
H_c — coercive force (oersteds)
I — steady-state current
i — instantaneous current
K — total thermal conductance
k_1 — thermal conductance per unit area of coil inner surface
k_2 — thermal conductance per unit area of coil outer surface
L_1 — single-turn inductance — $(4\pi/\mathcal{R}_1)$ or (ϕ/NI)
N — number of turns in coil

NI — steady-state ampere turns
Ni — just operate or just release ampere turns
NI_c — ampere-turn coercive force — $(H_c l/0.4\pi)$
R — coil resistance
t — time
t_1 — waiting time
v — ratio of flux at time t to steady-state flux
W — power — I^2R
$\mathfrak{F}$ — magnetomotive force — $4\pi NI$ or $\mathcal{R}\phi$
l — length of magnetic path
$\mathcal{R}$ — reluctance of relay
$\mathcal{R}_c$ — reluctance of core
$\mathcal{R}_r$ — initial incremental reluctance
ϕ — flux
ϕ_1 — steady-state flux
ϕ'' — saturation flux
ϕ_0 — residual flux
θ_0 — ambient temperature
$\bar{\theta}$ — mean coil temperature.

5.2 *General*

Since the only change proposed in the relay is the core material, the armature, contact springs, balance spring and other operating parts will be unchanged. The mass and spring forces of these parts control the travel time of the relay in both the operate and release directions. The change in core material will, because of a different eddy current conductance, affect only the electrical waiting time of the relay. Therefore, the electrical waiting time on the operate and then on the release of the relay will be considered first.

5.2.1 *Electrical Waiting Time — Operate*

The electrical waiting time on operate of a relay is defined as the time from the application of potential to the relay coil until the magnetic pull on the armature equals the back force on the armature and it starts to move. During this period the flux development in the structure follows the relationship:

$$\mathfrak{F} - \mathfrak{F}_s + 4\pi G \frac{d\phi}{dt} = 0 \tag{1}$$

where $\mathfrak{F}_s$ is the steady-state magnetomotive force (mmf) or $4\pi NI$, $\mathfrak{F}$

is the effective mmf and is equal to $\mathcal{R}\phi$, and G is equal to the coil conductance (G_c) plus the eddy current conductance (G_e). The reluctance ($\mathcal{R}$)is a function of the armature-core air gap (X) and the flux (ϕ). With the armature at rest against the back stop and using the initial conditions X_1 and $\mathcal{R}_1$, (1) can be rewritten in the integral form with $\phi_1\mathcal{R}_1$ substituted for $\mathfrak{F}_s$ as follows:

$$t_1 = \frac{4\pi G}{\mathcal{R}_1} \int_0^{\phi} \frac{d\phi}{\phi_1 - \phi} \tag{2}$$

which on integration gives:

$$t_1 = \frac{4\pi G}{\mathcal{R}_1} \ln \frac{1}{1 - v}. \tag{3}$$

Since v, the ratio of flux attained at time t to the steady-state flux, can be written as the ratio of the just operate ampere turns to the steady-state ampere turns Ni/NI, and $4\pi/\mathcal{R}_1$ is equal to L_1, the single-turn inductance, (3) may be rewritten as follows:

$$t_1 = L_1(G_c + G_e) \ln \frac{1}{1 - (Ni/NI)} \tag{4}$$

which is the general form of the equation for the electrical waiting time of a relay on operate.

5.2.2 *Electrical Waiting Time — Release*

The release waiting time of a relay is defined as the time from the opening of the coil circuit to the beginning of motion of the armature from the operated position. The opening of the circuit results in a decaying magnetic field which is sustained only by eddy currents. The release waiting time is described by the same relationship as the operate waiting time except that since $\mathfrak{F}_s = 0$ with the coil circuit open (1) becomes:

$$\mathfrak{F} + 4\pi G \frac{d\phi}{dt} = 0. \tag{5}$$

The normal-release waiting time of a relay without copper sleeves can only be determined approximately because of the variable distribution of the magnetic field sustained only by eddy currents (G_e). However, if the flux decay is retarded by the introduction of a conductance much larger than G_e, such as a copper sleeve or short-circuited coil turns, the decaying field is nearly uniform and a relatively close approximation to (5) can be made. Equations thus derived for the slow-release case can be used for the approximate analysis of the normal-release time case. Then (5) can be written in the integral form:

$$t_1 = 4\pi G \int_{\phi}^{\phi_1} \frac{d\phi}{\mathfrak{F}} \tag{6}$$

where t_1 is the waiting time for the flux to decay from the steady-state value (ϕ_1) to the value (ϕ) at which the magnetic pull is equal to the retractile force.

For reliable and repetitive release times, the steady-state flux (ϕ_1) of a relay should be in the region of flux saturation (ϕ''). Therefore, release times will only be considered from this condition. Since $\mathfrak{F} = \mathfrak{R}\phi$ and the relationship between ϕ and $\mathfrak{F}$ is in the demagnetization curve, the following equation results:

$$\mathfrak{F} = \frac{(\phi'' - \phi_0)(\phi - \phi_0)}{(\phi'' - \phi)} \mathfrak{R}_r \tag{7}$$

where $\mathfrak{R}_r$ is the incremental reluctance when $\mathfrak{F} = 0$.

If (7) is substituted in (6), the expression for release waiting time becomes:

$$t_1 = \frac{4\pi G}{\mathfrak{R}_r} \int_{\phi}^{\phi''} \left(\frac{1}{\phi - \phi_0} - \frac{1}{\phi'' - \phi_0} \right) d\phi. \tag{8}$$

Integration of this equation results in:

$$t_1 = \frac{4\pi G}{\mathfrak{R}_r} [\ln Z - 1 + (1/Z)], \tag{9}$$

where

$$Z = \frac{\phi'' - \phi_0}{\phi - \phi_0}.$$

To have a more readily usable relationship for release waiting time, it is necessary to obtain an expression for Z in terms of $\mathfrak{F}$ or $4\pi Ni$. Equation (7) can be rewritten to give the following expression for:

$$Z = 1 + \frac{\phi'' - \phi_0}{4\pi Ni} \mathfrak{R}_r . \tag{10}$$

Substituting the expression for $\mathfrak{R}_r$ as obtained from (10) in (9), and recognizing that with the coil circuit open and no sleeves or short-circuited turns the only conductance involved is the eddy current conductance (G_e), the following expression for release waiting time is obtained:

$$t_1 = \frac{G_e(\phi'' - \phi_0)}{Ni}\left(\frac{\ln Z}{Z - 1} - \frac{1}{Z}\right). \tag{11}$$

VI. EVALUATION OF OPERATE AND RELEASE WAITING TIME

Equations (4) and (11), for operate and release waiting times respectively, can be evaluated by obtaining values for the variables experimentally and graphically. In this section the procedures for the establishment of the relay parameters will be discussed.

The first data needed are magnetization curves of flux vs ampere turns with the armature in the unoperated position for the evaluation of operate waiting time and in the operated position for release waiting time. Typical curves are shown in Figs. 11 through 16 (see Section VIII). With measured values of just operate, just release and steady-state current, all of the flux values for (4) and (11) can be read from the curves. The inductance per turn (L_1) may be found by drawing a line through the origin of the unoperated magnetization curve tangent to the nearly flat or linear portion of the curve (see Fig. 5). The slope of the tangent is a reliable value for L_1 if the just operate flux falls on the linear portion of this curve.

Since G in (2) and (6) is equal to the sum of G_e and G_c, the effective eddy current conductance G_e can be determined reasonably well graphically and experimentally by holding the values of the integrals of the two equations fixed and making timing measurements as G_c, which is equal

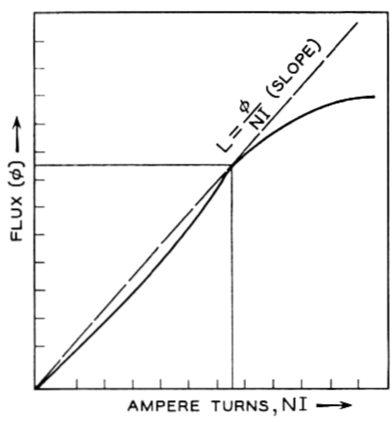

Fig. 5 — Inductance per turn (L_1) from magnetization curves.

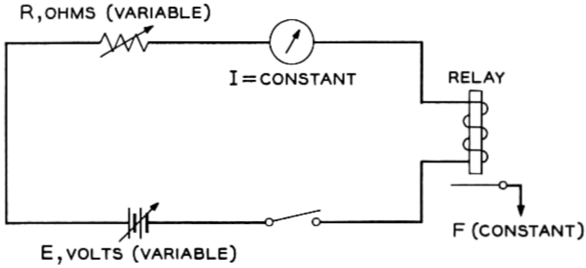

Fig. 6 — Circuit for varying G_c or N^2/R by changing R (coil in operate condition).

to N^2/R, is varied. A fixed value for either integral can be assured by having the relay adjusted so that its steady-state current and either just operate or just release current are maintained constant throughout the experiment. G_c or N^2/R can then be varied by changing the resistance in series with the coil as shown in Fig. 6 for the operate condition and Fig. 7 for the release condition. Since all factors except G_c are held constant, a plot of G_c versus waiting time will be linear, and when extrapolated to $t = 0$ will have a negative intercept on the G_c axis equal to G_e as shown in Fig. 8.

Values for all of the variables in (4) and (11) were determined for both one-piece 1 per cent silicon steel cores and laminated S.A.E. 1010 steel cores and the waiting time for operate and release computed. The computed values are compared to measured values in a later section.

VII. EXPERIMENTAL DETERMINATION OF OPERATE AND RELEASE TIMES

In production, permissible dimensional tolerances of the parts and differences in the magnetic characteristics of the cores due to material

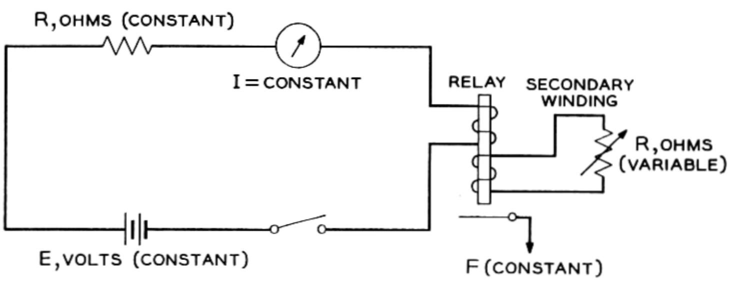

Fig. 7 — Circuit for varying G_c or N^2/R by changing R (coil in release condition).

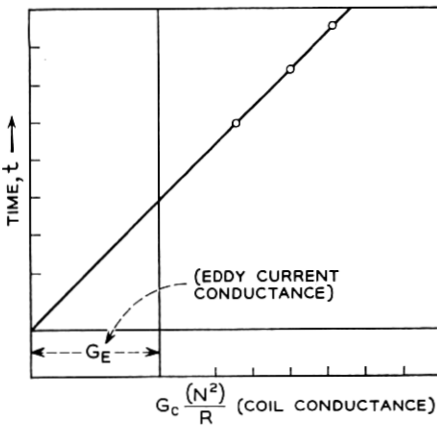

Fig. 8 — Waiting time vs coil conductance.

and annealing variations will result in variations in the operational characteristics of the relays. To evaluate these effects, two sample groups of relays with each core material were constructed. Group SP was made with minimum-dimension parts having a poor anneal and group LG had maximum-dimension parts with a good anneal. Fig. 9 shows the operate time of these relays as a function of coil conductance with an unoperated air gap of 0.032 inch and with input powers of 2 and 10 watts. It will be noted that the laminated S.A.E. 1010 steel core relays are approximately 1.3 to 3.4 per cent faster than the 1 per cent silicon steel core relays.

Fig. 10 shows the release times and release pull values for the same groups of relays. Here, it is noted that the laminated S.A.E. 1010 steel core relays release from 13 to 27 per cent faster than the 1 per cent silicon steel core relays.

VIII. COMPARISON OF CALCULATED AND MEASURED TIMES

The measured times shown in Figs. 9 and 10 all include some armature movement. However, all of the relays had essentially the same mechanical adjustments, and the same SP and LG armatures were used on both the laminated S.A.E. 1010 steel and 1 per cent silicon steel cores. Therefore, it can be assumed that the mechanical armature travel times of the relays were essentially the same. As a result, a comparison of like sets of relays, i.e., SP laminated versus SP one-piece, etc., should reflect the difference in electrical waiting time of the groups being compared.

A comparison of the calculated times for the like sets of relays was also made using the values of L, G_e, ϕ, ϕ_0, etc., obtained from Figs. 11

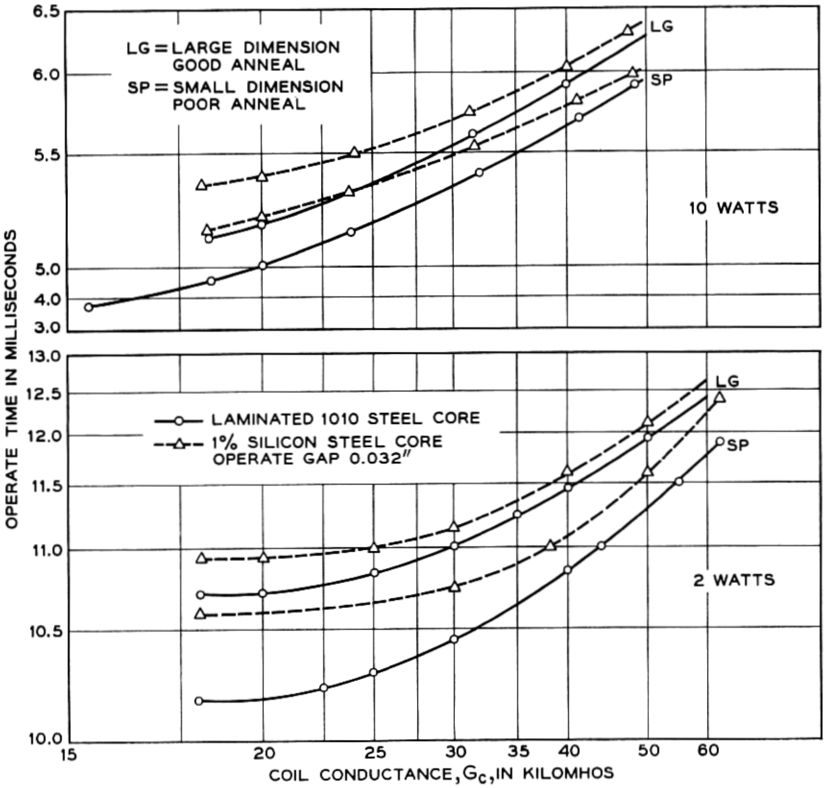

Fig. 9 — Change in relay operate time due to variation in relay dimensions and quality of anneal. Relays had cores of either laminated 1010 steel or 1% silicon steel.

through 16 as described earlier. Tables I and II show the comparison between the laminated S.A.E. 1010 core relays and the 1 per cent silicon steel core relays as determined by measurement and by calculation. In all cases good agreement was found between the measured and calculated values.

IX. COMPARISON OF EDDY CURRENT CONDUCTANCE

In Tables I and II are listed the values of eddy current conductance obtained for the SP and LG groups of relays. 7.20 and 8.25 kilomhos respectively were found for the 1 per cent silicon steel cores and 5.55 and 6.65 kilomhos respectively were found for the laminated S.A.E. 1010 steel cores. Since the S.A.E. 1010 steel has approximately twice the con-

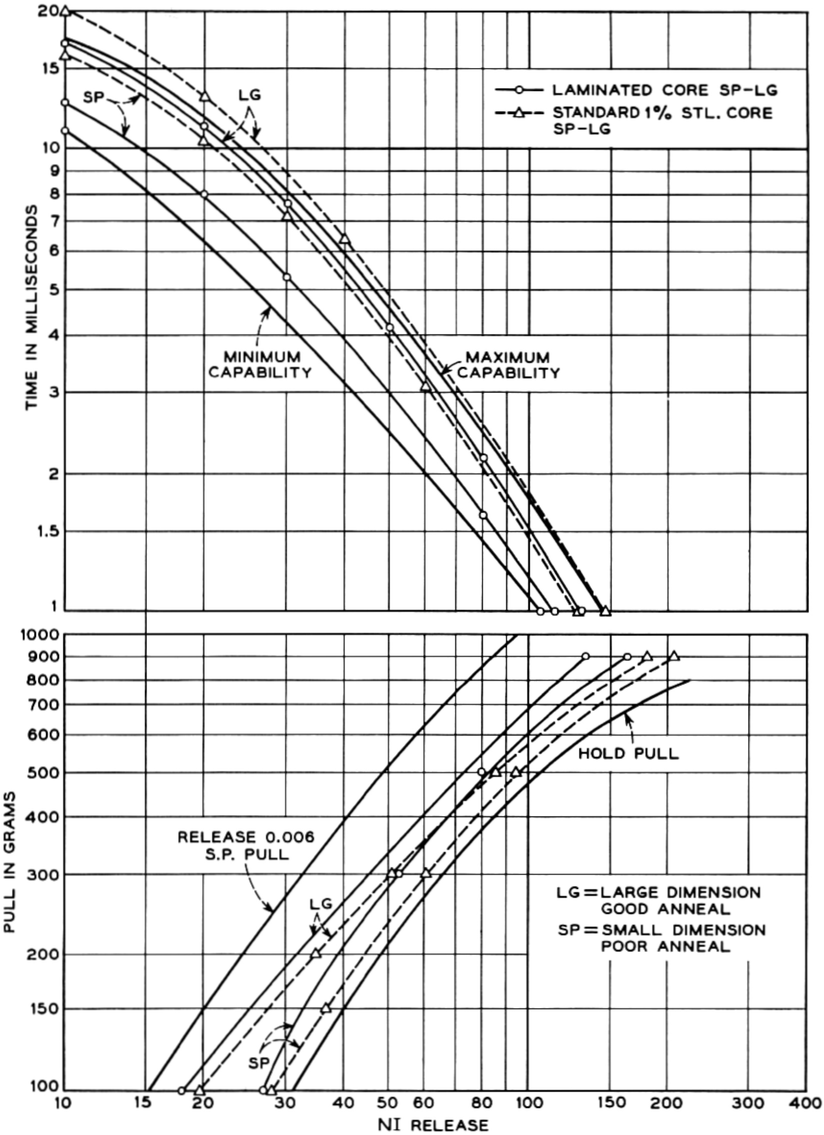

Fig. 10 — Release pull values (grams) and release times (ms) for relays with cores differing in dimension, quality of anneal, and type of steel used.

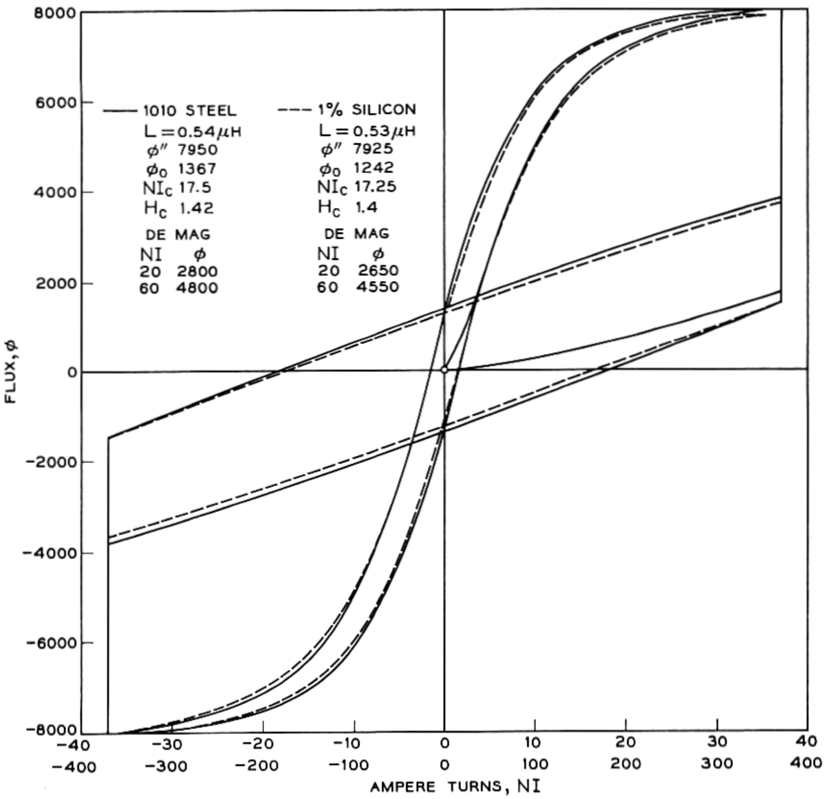

Fig. 11 — Magnetization curves of cores with small dimensions and poor anneal (0.006 air gap).

ductivity of 1 per cent silicon steel, the eddy current conductance of the S.A.E. 1010 cores would have been about 14.4 and 16.5 kilomhos for the SP and LG groups respectively if the cores had not been laminated. Thus laminating reduced the eddy current conductance of the cores by the ratios of 5.55/14.4 or 38.5 per cent for the SP group of relays and 6.65/16.5 or 40.3 per cent for the LG group of relays. Since it was expected that the use of two laminations would reduce the effective eddy current conductance by a ratio of between $1/N$ and $1/N^{\frac{3}{2}}$ or between 50 and 35.4 per cent, good agreement with the theoretical analysis is indicated.

X. COIL HEATING (POWER INPUT VS TEMPERATURE RISE)

Another major consideration is the effect of using a laminated core and a new material on the dissipation of heat from the relay coil. The

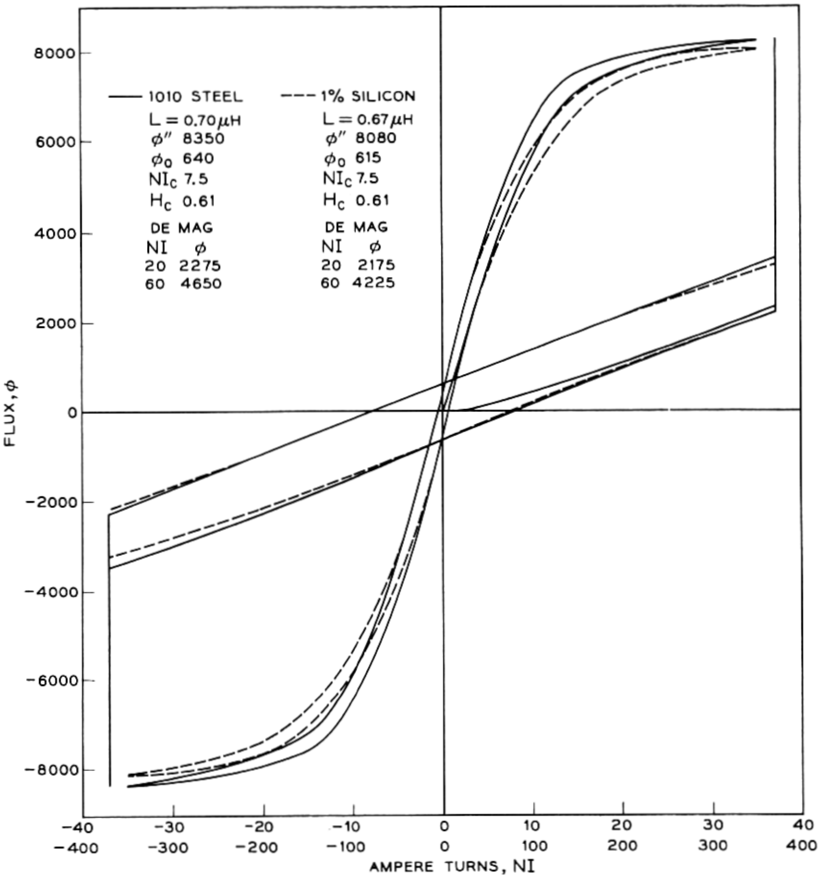

Fig. 12 — Magnetization curves of cores with large dimensions and good anneal (0.006 air gap).

allowable mean temperature rise of a relay coil is limited by two factors. The first of these is that in normal operation the temperatures should not rise to a point that is dangerous to personnel in case of physical contact. This limit has been established for many years in the Bell System at 225°F. The temperature rise in normal operation is a function of the duty cycle of the relay and is influenced, therefore, by its circuit application. The second limitation on temperature rise — that the relay shall not become a fire hazard in case of indefinite energization — is of more direct interest from an apparatus standpoint. With the normal wire insulations and coil insulating materials used in Bell System relays, it has been found that a maximum mean coil temperature of 360°F can

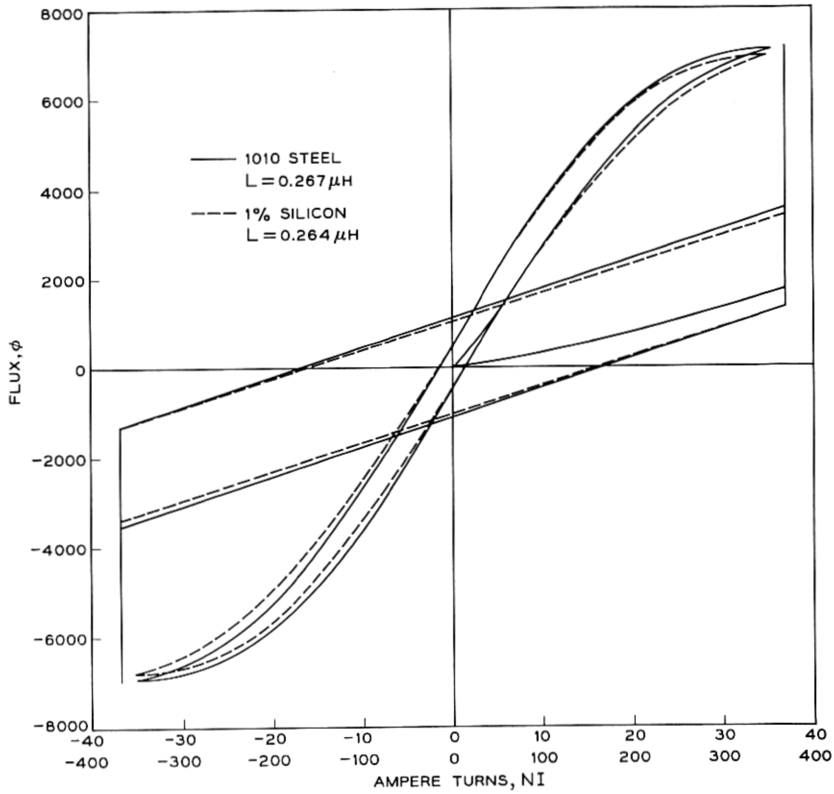

Fig. 13 — Magnetization curves of cores with small dimensions and poor anneal (0.032 air gap).

be allowed with essentially no risk of insulation breakdown which would produce a fire hazard. It is recognized, though, that prolonged exposure of a relay to such a temperature could result in permanent damage.

The dissipation of heat from a relay coil occurs mainly from the inner and outer surfaces by a combination of conduction, convection and radiation, with negligible dissipation at the coil ends. Convection and radiation are principal factors at the outer surface and conduction through the insulation and core is the principal factor at the inner surface.

The dissipation of heat is therefore through parallel paths which can be represented by the electrical circuit analogy shown in Fig. 17. The imposed voltage is equivalent to the temperature difference between the coil and ambient, the electrical current is equivalent to the heat

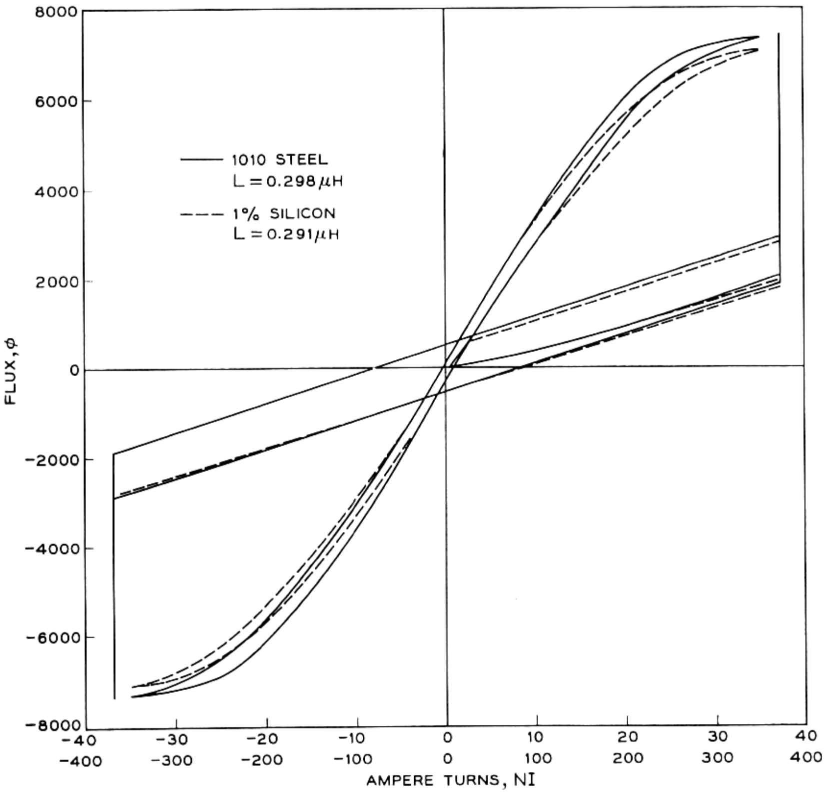

Fig. 14 — Magnetization curves of cores with large dimensions and good anneal (0.032 air gap).

flow in the branches, and the electrical conductance is equivalent to the heat conductance. As shown in Fig. 17, there is a circuit of two branches: one from the coil through the outer core surface to ambient and the other from the coil through the inner coil surface and the core to ambient.

From this analogy it has been found that a good approximation of the mean coil temperature can be obtained from the relationships:

$$K = k_2 a_2 + \cfrac{1}{R_c + \cfrac{1}{k_1 a_1}} \tag{12}$$

and

$$\frac{E^2}{R_0} = K(\bar{\theta} - \theta_0)\left(1 + \frac{\bar{\theta} - \theta_0}{390 + \theta_0}\right) \tag{13}$$

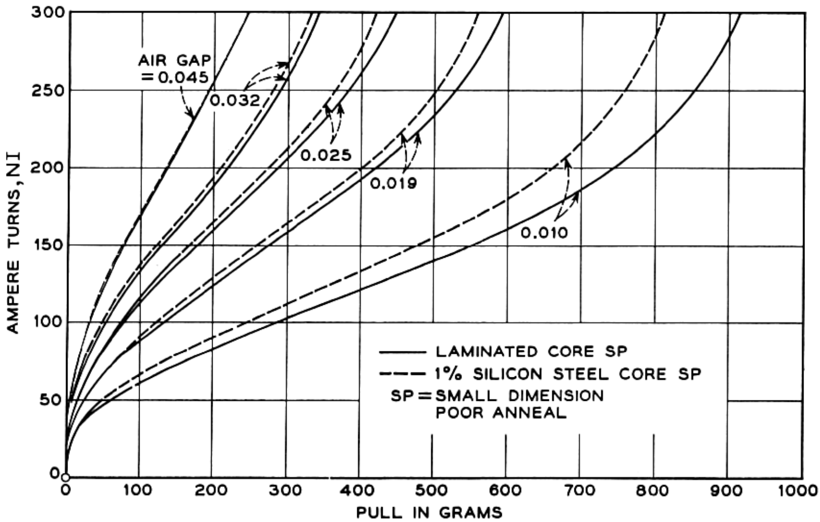

Fig. 15 — Ampere turns vs operate pull values for cores with small dimensions and poor anneal.

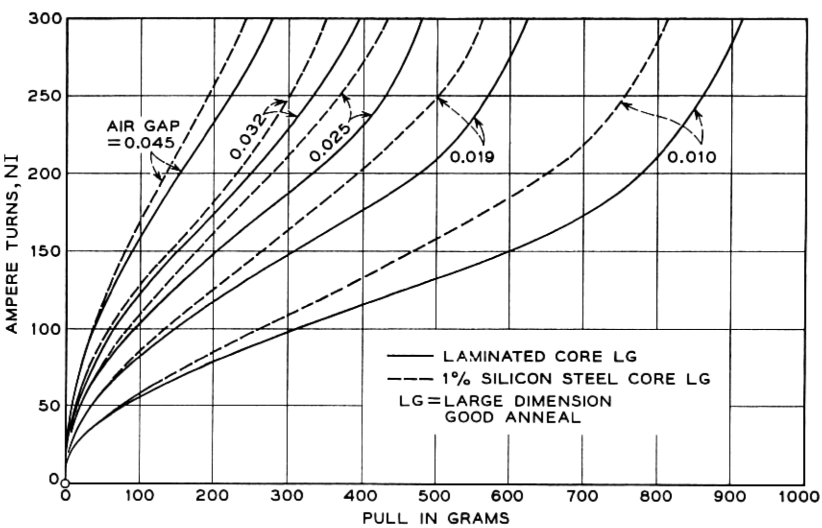

Fig. 16 — Ampere turns vs operate pull values for cores with large dimensions and good anneal.

TABLE I — EFFECT OF USING LAMINATED CORES ON EDDY CURRENT CONDUCTANCE AND OPERATE TIMES

Relay Dimensions	Core		L μH	G_e Kmho	Per Cent Decrease in Operate Times — t_L (laminated core) vs t_s (1% silicon core)							
					2 watts $G_c = 25$ Kmho		2 watts $G_c = 40$ Kmho		10 Watts $G_c = 25$ Kmho		10 watts $G_c = 40$ Kmho	
	Material	Type			Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.
SP	SAE 1010	lam.	0.267	5.55	3.7%	3.3%	2.5%	2.8%	3.4%	3.4%	2.3%	2.1%
SP	1% silicon	solid	0.264	7.20								
LG	SAE 1010	lam.	0.298	6.65	2.3%	2.8%	1.1%	1.3%	2.3%	2.7%	3.5%	3.3%
LG	1% silicon	solid	0.291	8.25								

TABLE II — EFFECT OF USING LAMINATED CORES ON EDDY CURRENT CONDUCTANCE AND RELEASE TIMES

Relay Dimension	Core		G_e Kmho	Per Cent Decrease in Release Times — t_L (laminated core) vs t_s (1% silicon core)			
				20 Ni Release		60 Ni Release	
	Material	Type		Calc.	Meas.	Cal.	Meas.
SP	SAE 1010	lam.	5.55	24%	25%	27%	27%
SP	1% silicon	solid	7.20				
LG	SAE 1010	lam.	6.65	16%	13%	19%	14%
LG	1% silicon	solid	8.25				

where R_c = the thermal resistance of the core in "Fahrenheit ohms,"
R_0 = the coil resistance at ambient temperature,
θ_0 and $\bar{\theta}$ are expressed in degrees Fahrenheit
and other symbols are as defined earlier.

The exact thermal conductance of complete relay structures will vary

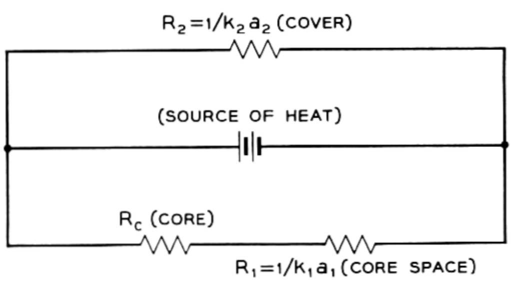

Fig. 17 — Electrical circuit analogy of dissipation of heat.

considerably from unit to unit because of variations in relay assembly, such as the tightness of fit of the coil on the core. However, nominal values for a_1, a_2, k_1, k_2, and R_c have been established for general-purpose wire spring relays with 1 per cent silicon steel cores. These values along with the theoretical difference in R_c for laminated S.A.E. 1010 steel cores can be used to calculate mean coil temperatures. The established mean values are as follows:

$$k_1 = 0.01 \text{ watt/F}^\circ/\text{in.}^2$$

$$k_2 = 0.0055 \text{ watt/F}^\circ/\text{in.}^2$$

$$a_1 = 2.32 \text{ in.}^2$$

$$a_2 = 5.54 \text{ in.}^2$$

$$R_{cs} = 35 \text{ Fahrenheit ohms (solid 1 per cent silicon steel core).}$$

Then with an applied voltage of 100 volts dc, a coil resistance of 1451 ohms, and an ambient temperature of 77°F, the mean coil temperature of a relay with a 1 per cent silicon steel core was calculated as follows:

$$k_1a_1 = 0.0232 \text{ watt/F}^\circ$$

$$k_2a_2 = 0.0304 \text{ watt/F}^\circ$$

$$K_s = k_2a_2 + \frac{1}{R_{cs} + \dfrac{1}{k_1a_1}} = 0.0304 + \frac{1}{35 + \dfrac{1}{0.0232}} = 0.0432 \text{ watts/F}^\circ$$

and

$$\frac{E^2}{R_0} = K_s(\bar{\theta} - \theta_0)\left(1 + \frac{\bar{\theta} - \theta_0}{390 + \theta_0}\right)$$

$$\frac{(100)^2}{1451} = 0.0432(\bar{\theta} - 77)\left(1 + \frac{\bar{\theta} - 77}{390 + 77}\right)$$

$$\bar{\theta}_s = 204^\circ\text{F (1 per cent silicon steel core).}$$

The mean thermal conductivity of S.A.E. 1010 is 53 watts/C°/cm² while the mean thermal conductivity of 1 per cent silicon steel is 28 watts/C°/cm², so that they are in a ratio of 53/28 or 1.89.

$$\therefore\ R_{c1} = \frac{35}{1.89} = 18.5 \text{ Fahrenheit ohms}$$

for S.A.E. 1010 steel cores. With the value of R_{c1} for S.A.E. 1010 steel cores and the other constants with the same as above, except that with this core the coil resistance was 1443 ohms, the mean coil temperature was calculated as follows:

$$K_1 = 0.0304 + \frac{1}{18.5 + \frac{1}{0.0232}} = 0.0467 \text{ watt/F°}$$

and

$$\frac{(100)^2}{1443} = 0.0467(\bar{\theta} - 77)\left(1 + \frac{\bar{\theta} - 77}{390 + 77}\right)$$

$$\bar{\theta}_1 = 195\text{°F (laminated S.A.E. 1010 steel core).}$$

For confirmation, heat tests were conducted on sample relays with both types of cores using applied voltages of 50 and 100 volts dc. Fig. 18 shows the mean coil temperature as a function of time. With an applied potential of 100 volts dc the calculated mean coil temperatures are 204°F and 195°F for the 1 per cent silicon steel and S.A.E. 1010 steel cores respectively, while the measured values are 205.5°F and 199.5°F in the same order. Thus the measured values are found to be in close agreement with the calculated values. Although there is nearly a two-to-one ratio between the thermal conductances of the two materials, there is only a 3 to 4 per cent difference in the mean coil temperatures. However, this small difference is in favor of the relays with laminated S.A.E. 1010 steel cores.

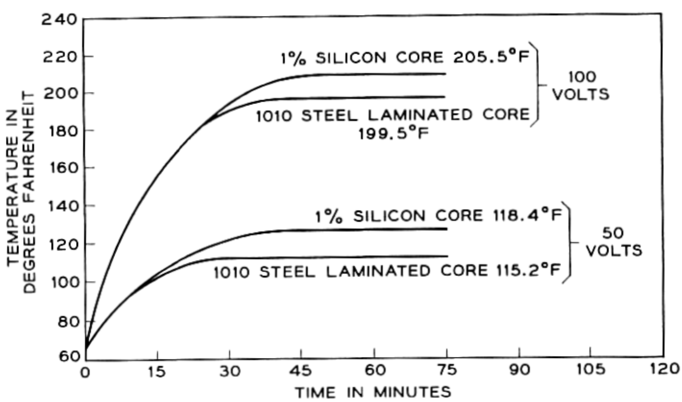

Fig. 18 — Mean coil temperature vs time.

XI. OPERATING LIFE

Since S.A.E. 1010 steel is softer than 1 per cent silicon steel, life tests were conducted to determine whether relays with laminated low-carbon steel cores have at least as long an operating life as currently manufactured relays. In operation, the armature stop disks and the hinge spring at the heel of the armature wear or pound into the core (see Fig. 19). If significant wear occurs at either of these points, it will cause a corresponding reduction in the release current and an increase in release time.

Fig. 20 shows the measured wear at the armature heel and the change in release time as a function of the number of operations. It is noted that the wear of the laminated S.A.E. 1010 steel cores is about equal to or less than that of the 1 per cent silicon steel cores. This is probably due to the lack of abrasiveness of the low-carbon steel as compared to the silicon steel after the finish has been worn through.

XII. CORE PLATE ASSEMBLY

The core plate of the relay (see Figs. 1 and 19) serves as a back stop for the armature, a positioning stop for the fixed contact molded block, an aligning fixture for the three core legs and a means of mass adjustment of the contacts. Therefore, it is essential that the core plate be securely fastened in place. The core plate is held in place by staking the ends of the two outer legs of the core as shown in Fig. 19. Tests show that the pull-off force of the core plate on the laminated low-carbon steel cores is approximately twice that of the pull-off force from silicon steel

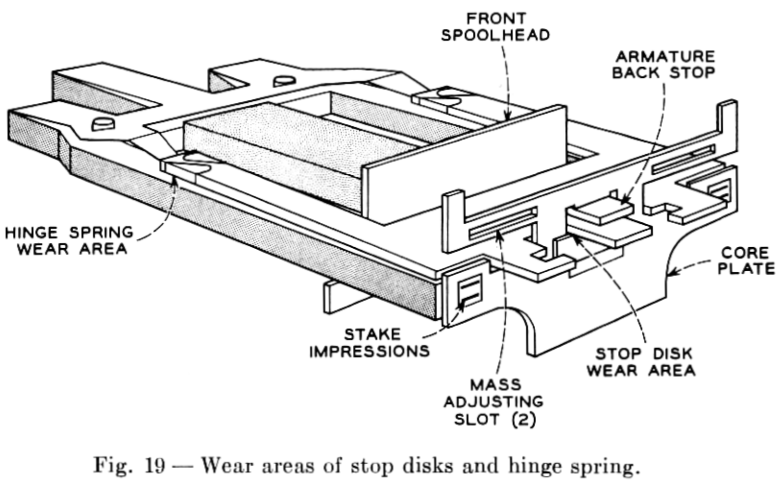

Fig. 19 — Wear areas of stop disks and hinge spring.

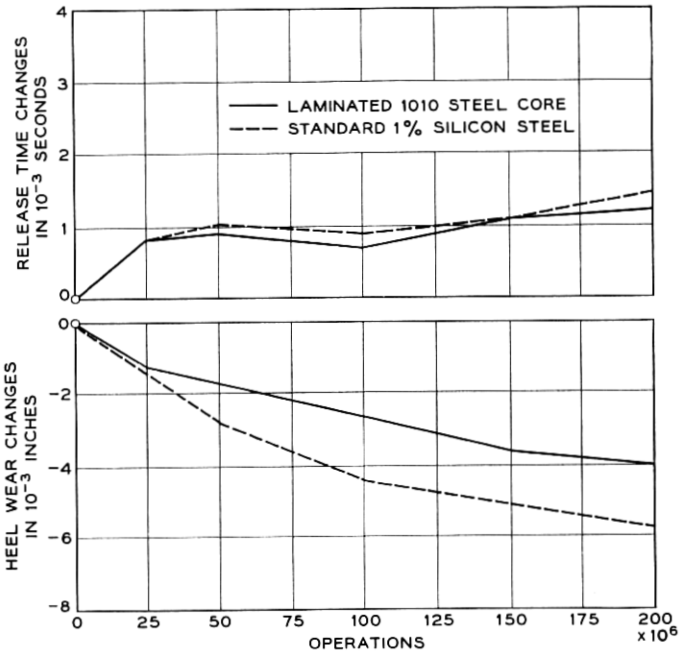

Fig. 20 — Heel wear and release time vs number of operations.

cores. The softer S.A.E. 1010 steel is upset more by the staking operation than the harder 1 per cent silicon steel.

XIII. CORROSION PROTECTION

If the two laminations were to be welded together immediately after punching, it was deemed necessary to establish the reliability of corrosion protection, along the laminated seam, obtained with the standard zinc-chromate finish on such an assembly. Therefore, a number of laminated core assemblies of S.A.E. 1010 steel were punched and welded together, magnetically annealed and then plated in the normal manner. The laminated assemblies, along with standard zinc-chromate plated 1 per cent silicon steel cores, were subjected to extensive corrosion studies under extremes of temperature and humidity. The extent of corrosion on both materials was within tolerable limits.

XIV. MANUFACTURING FACTORS

The manufacture of a relay with a two-piece laminated core presents a number of problems of dimensional control and parts handling which must be overcome before its introduction is economically feasible. Close dimensional control of core thickness is necessary in the areas where the front coil spoolhead and core plate are mounted, to assure tight and stable assemblies (see Figs. 4 and 19). With the one-piece core the thickness dimensions in these areas are controlled accurately by a squeezing operation on the part as the last step of the fabrication. With two separate laminations these areas would require closer control of the material thickness and the depressed areas, since with two parts fabricated separately the thickness tolerances would be additive on assembly.

A proposal to overcome this problem was suggested (see Fig. 21) in which one lamination is undercut so that only the thickness of one lamination appears in the critical areas. This would require a redesign of the core plate and spoolhead to fit the new core. Tests of sample relays with cores of this design revealed an appreciable degradation in pull and time characteristics.

An alternate proposal was suggested whereby two strips of S.A.E. 1010 steel are welded together at prearranged locations and then punched simultaneously as a single part. The welds between the two sheets are located so that after punching they appear on the core at the locations shown in Fig. 3. With this method of welding and punching, the two laminations of a core remain together throughout the fabrication proc-

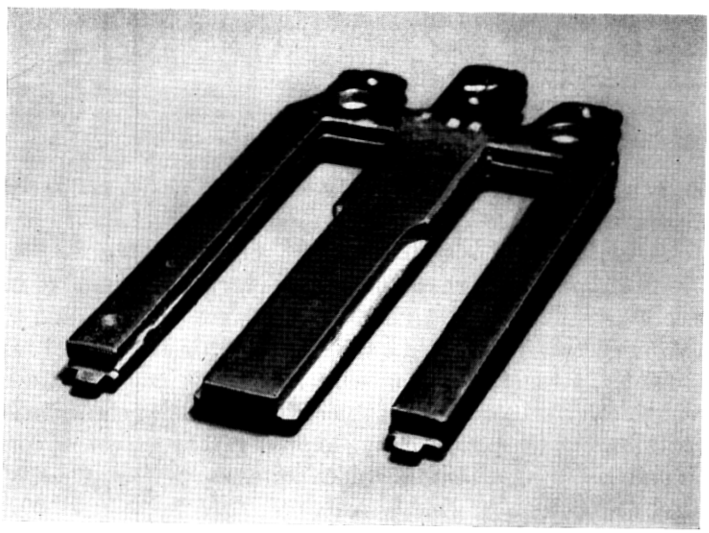

Fig. 21 — SAE 1010 steel laminated cores for general-purpose relays (rejected design).

ess, and the assembly is flattened and squeezed to size in the same operation as is now used with the one-piece core. Fig. 22 shows the two laminations without welding in the upper view, and a welded laminated core compared to a one-piece core in the lower view. Fig. 23 shows a schematic layout of the proposed process of welding the strip and punching the cores.

There is no appreciable difference in the operational quality of these

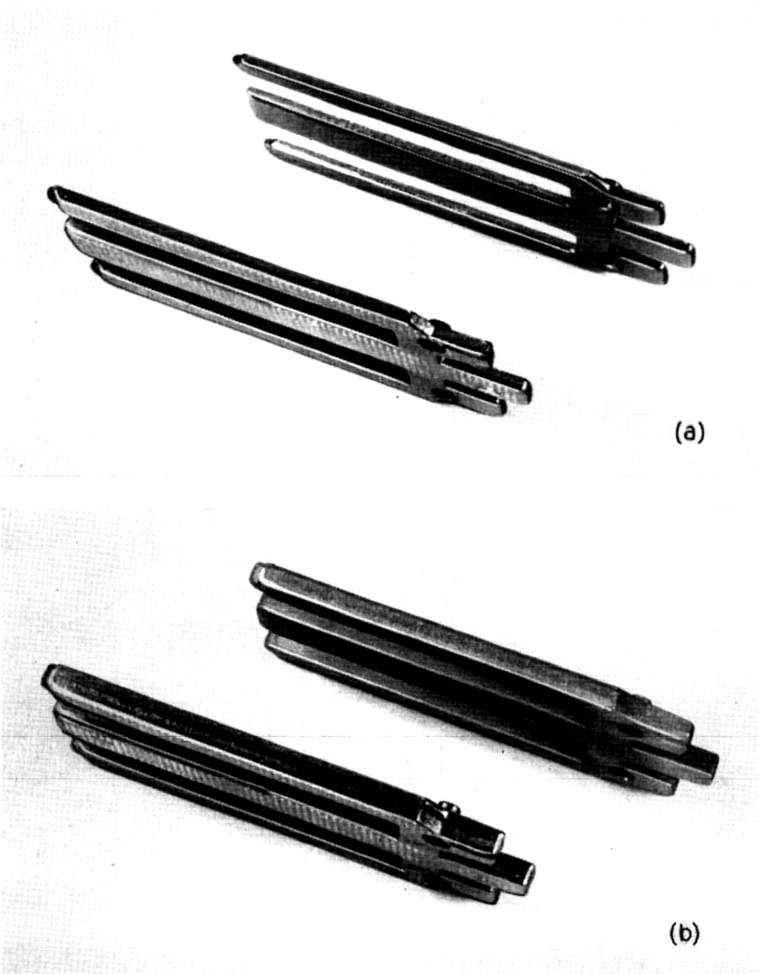

Fig. 22 — (a) Two core laminations before welding; (b) a welded laminated core compared to a one-piece core.

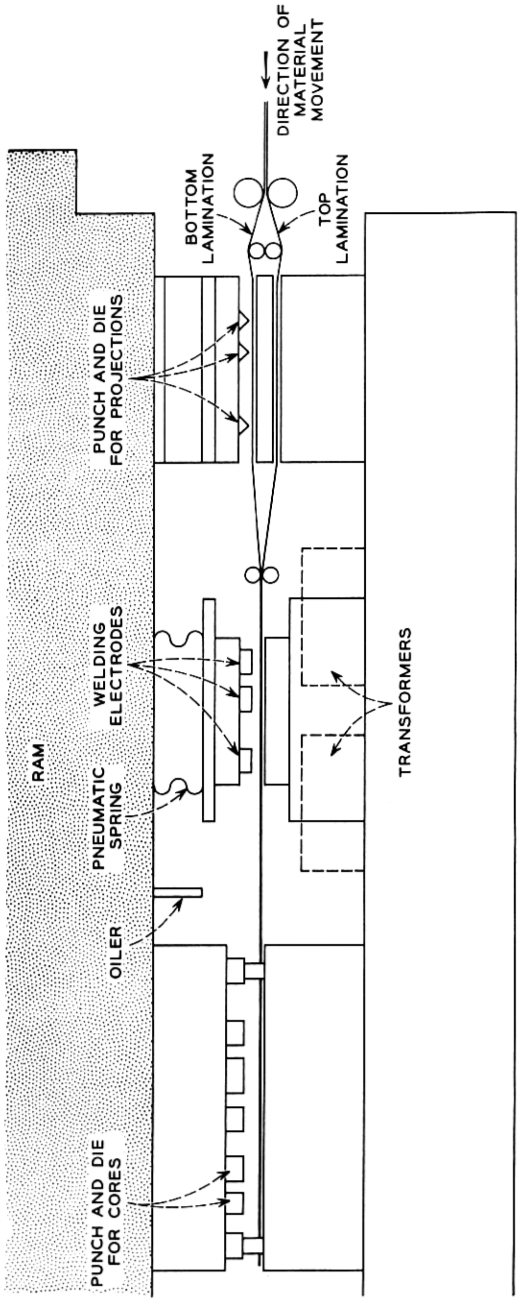

Fig. 23 — Schematic layout of the proposed process of welding the strip and punching the core.

relays whether the core laminations are welded or not. Therefore, the ultimate design in this respect will be determined by manufacturing considerations.

XV. SUMMARY AND CONCLUSIONS

(1) Wire spring relays made with laminated 1010 steel cores are at least as good as and in some respects better than the present standard 1 per cent silicon steel core relays.

(2) Operate times of the proposed laminated 1010 steel core relays are in general slightly faster than those of the present one-piece silicon steel core relays (1.3–3.4 per cent).

(3) Release times of the proposed laminated low carbon steel core relays are considerably faster than those of the present silicon core relays (13–27 per cent).

(4) Heat studies indicate slightly better heat dissipating qualities in the laminated core relays than in the present silicon steel core relays.

(5) Core plates are tighter on the laminated 1010 steel core relays than on the present silicon steel core relays.

(6) Resistance to corrosion with the present finish (zinc chromate) is as good on the laminated 1010 steel core design as on the one-piece silicon steel core design.

(7) Life tests show that the laminated low carbon steel cores are at least as resistant to wear as the present silicon steel cores.

(8) Substantial manufacturing savings can be realized by changing to the laminated 1010 steel core for the general-purpose wire spring relay.

XVI. ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance given by J. A. Cooper, J. J. Dunbar, F. J. Gibson and E. R. Priday in obtaining the data used and C. B. Brown and H. M. Knapp for the helpful suggestions in the preparation of this article.

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