Magnetic Latching Crossbar Switches:

A New Development in Magnetic Properties of Tool Steel

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A magnetic latching function in crossbar switch hold magnets is obtained by means of a specially designed magnet core made of high-carbon tool steel. The fabricated core detail is given a hardening heat-treating cycle, regulated to produce a particular degree of physical hardness that was found to impart the optimum combination of magnetic properties needed to obtain pulse operation and magnetic latching of the electromagnet under a wide range of contact spring loads. The nominal latching force developed with this new electromagnet design is 4 lbs, with a cylindrical core of only 0.11 square inch cross-sectional area. The electrical operating power need be only 2.5 watts applied for 0.100 second or about 18.0 watts for 0.015 second, and the reverse release pulse strength is about 50 per cent of the operate value. The coexisting values of coercive force, residual induction and magnetic permeabilities obtained in this design are new and useful to the art of designing electromagnetic switching devices with a magnetic latching function.

I. INTRODUCTION

Since the introduction of the dial-type telephone switching systems, switching devices such as relays and electromagnets have become the most essential and widely used of all the components in the telephone central office. Many notable improvements on these switching devices have made it possible for the telephone systems to grow and serve the increasing population of customers. The advancements on these devices have dealt largely with their sensitivity and speed of operation, contact switching capacity, service life and reliability. In contrast to these improvements, however, it appears that very little has been done to save operating power by utilizing residual magnetic energy to effectively hold the electromagnets in the operated position without continuous current drain. Recently, however, a new electromagnet core design that provides this function was developed for crossbar switch hold magnets. This utilizes a new combination of magnetic properties that have been found to exist in high carbon steel after it has undergone a suitable hardening heat-treating cycle.

There are no mechanical locking features associated with this new magnetic latching hold-magnet design. The magnetic latching force developed at the termination of the short electrical operating pulse is obtained solely by the efficient use of the residual magnetic induction and coercive force properties of the new magnet core. To restore the electromagnet to its nonoperated position, it is only necessary to re-energize the magnet coil with another short pulse of lower current strength and opposite polarity.

The total amount of electrical power necessary to energize the magnetic latching hold magnet is about 2.5 watts applied for only 0.100 second. Since many hold magnets must hold during each telephone conversation, this represents a very large power saving compared to the power used by the present nonlatching hold magnets. This design of magnetic latching hold magnets makes it possible to use 100- and 200-crosspoint crossbar switches in remote locations where the power supply is very small compared to that in a central office. A notable application of this new magnet core development is the conversion of existing crossbar switch hold magnets to magnetic latching operation, as might be used in telephone line concentrators.

II. NEED FOR A NEW MAGNET CORE MATERIAL

The state of the art in the design of electromagnets and the processing of associated magnetic materials for useful magnetic properties has advanced with many notable improvements during the past thirty years. It is of interest to observe the direction that some of the improvements in magnetic materials have taken in relation to what is required for magnetic latching functions.

In the class of soft magnetic materials, such as the magnetic irons and low carbon steels normally used for relays and electromagnets, the effort has been directed mainly toward greater permeability and associated reduction of coercive force. Since this is in the direction of reducing the quantity of the stored electromagnetic energy, usually represented by the product of the coercive force and remanence, this class of materials is definitely not suitable for a magnetic latching function. The property of low coercive force and associated greater permeability, of course, is very useful for obtaining greater operating sensitivity and greater release-to-operate ratios.

In the class of hard magnetic materials normally used for permanent magnets, the effort has been directed to increase the coercive force, even at the expense of a reduction in remanence, as long as the result was an increase in the numerical value of the product of coercive force in oersteds and remanence in gausses. In spite of the high values of magnetic energy that can be stored in them, permanent magnet materials would not be satisfactory in the core of a magnetic latching electromagnet, primarily because the required operating power would be several times as high as is practical in switching circuits. In general, this is due to the inherent high magnetic reluctance or low magnetic permeability of hard magnetic materials that are processed to be permanent magnets. Magnet cores that are made from materials commonly used for permanent magnets are therefore not conducive to efficient magnetic latching designs, especially when the contact spring loads on the same electromagnet range from small to large values from one operation to another, as they do in crossbar switch hold magnets. The required range of contact spring loads will be described later.

It appears, therefore, that past developments in magnetic materials have not been in the direction of producing a high order of quality in both operating and magnetic latching properties. The development of an economical and workable magnetic latching hold magnet design required the development of new coexisting combination of values of permeability, coercive force and remanence in a suitable magnet core material. A description of this development and the resulting operating capabilities of the magnetic latching crossbar switches that have been designed for new telephone equipment will be given, with special emphasis on the essential electromagnet design principles that guided this development.

III. BASIC FACTORS GOVERNING DESIGN OF THE LATCHING MAGNET

The combination of magnetic properties that must be obtained in the magnetic circuit of the electromagnet to satisfactorily meet the operating and latching functions is dependent upon the following primary factors:

i. the permissible mechanical form and size of the electromagnet and its switching functions;

ii. the range of contact spring loads to be applied to one magnet assembly;

iii. the range of the electrical pulses, in time and power values, available to operate and release the magnet.

It is therefore desirable to first describe these conditions, in order to follow the steps taken in the magnet core development.

3.1 *The Structure and Switching Functions of the Crossbar Switch Hold Magnet*

The magnetic latching hold-magnet design will be used for the same type of contact switching functions as those of the nonlatching hold magnets presently used in the crossbar switches of crossbar switching telephone systems, except that the loads will cover a wider range of values. As illustrated by Fig. 1, the hold magnet is the motor element of the vertical unit assembly. The latter, as its name implies, provides a vertical row of ten levels of crosspoint contacts, each level consisting of two to six pairs of make contact springs that are used for transmission and control circuit connections, and a separate assembly of hold-off normal contact springs (HON), consisting of two or three pairs of make or break contacts that are used for common control circuit connections.

The select magnets and vertical units are mechanically linked by horizontal select bars carrying flexible wire fingers that can be rotated through a small angle in either of two directions. The crossbar switch therefore represents a rectangular coordinate arrangement of 100 or 200 crosspoints, any one of which may be selected by the operation of

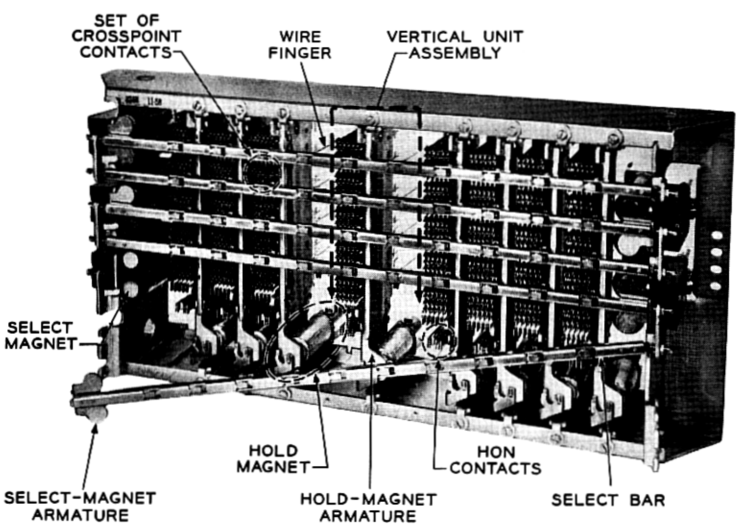

Fig. 1 — Crossbar switch, showing location of hold magnet as motor element of vertical unit assembly.

a particular select magnet and hold magnet. The total number of contacts that may be actuated by one hold magnet depends upon the circuit operating sequence of the select magnets in the crossbar switch, as described below.

The operation of a select magnet rotates the select bar associated with it, thereby interposing a wire finger between each hold magnet armature and the end of each card supporting the moving springs of each set of crosspoint contacts that lies in the horizontal level corresponding to the operated select magnet. Then the operation of a particular hold magnet determines which set of crosspoint contacts is selected in that horizontal level. Sometimes two select magnets are energized simultaneously in order to select one set of crosspoint contacts in each of two horizontal levels by the operation of one hold magnet. Sometimes the hold magnet is operated to switch the HON contacts without any crosspoint contacts. The quantitative values of the different contact spring loads that may be applied to one hold magnet are shown graphically in Fig. 2.

3.2 *Mechanical Load Forces Affecting the Design of the Magnet*

Each curve of Fig. 2 shows the rate at which the spring load builds up on the hold magnet armature, as the armature moves from the nonoperated position to the operated position against the core poleface. As indicated, the maximum crosspoint and HON contact spring load may build up to a value of 1150 grams and the minimum HON spring load may be only 140 grams. These individual load values are very important, because the new hold magnet design, to be successful, must be capable of operating, latching and releasing with any one of the load values, under any one of the extremes of the circuit operating power conditions.

There are two important magnetic requirements on the new magnet design that are affected by the maximum load build-up rate shown in Fig. 2. The first is that the magnetic force of attraction acting on the armature during its operating travel shall always exceed the force required to move the corresponding instantaneous load by a substantial amount. It is this differential, together with the electrical time constant of the magnet coil (the time rate of coil current development), that governs the operating or switching time of the electromagnet. The second requirement on the core is that the magnetic latching force shall always exceed by a substantial amount the force required to hold the maximum load of 1150 grams. It is this differential that governs the ability of the latched magnet to withstand disturbing forces that

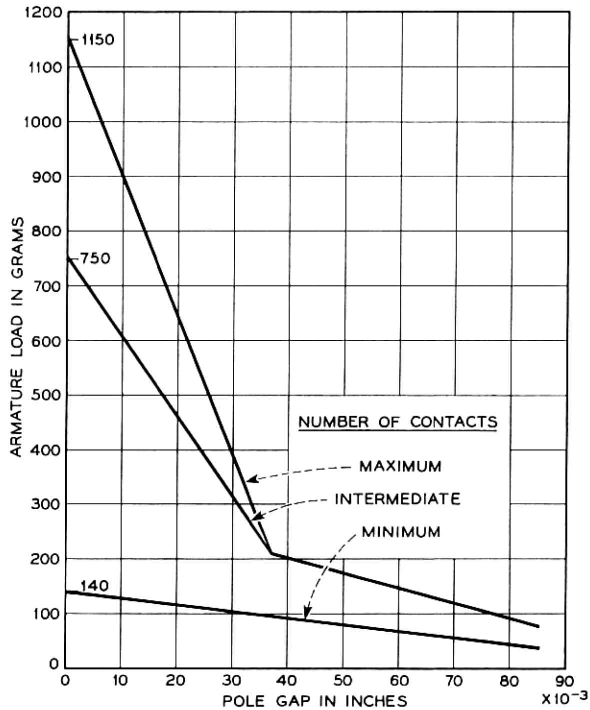

Fig. 2 — Range of contact spring loads on magnetic latching hold magnets.

may be developed by shock and vibration when the equipment is mounted on a telephone pole. If the disturbing vibrations should cause the armature to bounce or lift off the core poleface by only a fraction of one mill-inch, the spring load might then cause the premature release of the armature. More will be said later about the latching force margin, the disturbing forces and the effect of very small separations between the mating poleface surfaces.

The minimum load value of 140 grams is also an important consideration in the new magnet design, because it affects the permissible limits of the strength of the reverse release pulse that may be applied to the latched electromagnet without false reoperation. This means that the minimum electrical strength of the release pulse must be strong enough to always release the lightly loaded armature, but that the maximum pulse strength must not reoperate it. Failure to release or false reoperation are trouble conditions that must be guarded against in the magnetic latching design.

3.3 *Operate and Release Pulses Prescribed by the Circuit Conditions*

Since the electrical power available in some of the circuits that will use the new switches is limited, it was necessary to place a limit on the maximum current strength in the individual operating pulse for the magnetic latching magnet design. Circuit and equipment design considerations also determined the limiting values of the voltage and the time duration of the operating and releasing pulses. The limiting pulse values, insofar as they affect the magnet design, were set up, tentatively, to be as follows:

Energizing pulse: maximum 0.2 ampere at 22 to 28 volts for a minimum of 0.100 second;

Operating time (to switch all contacts): maximum 0.050 second;

Releasing time (to restore all contacts): maximum 0.050 second.

IV. DEVELOPMENT OF THE MAGNET CORE DESIGN

From the foregoing analysis of the work loads and the power available to perform the electrical operate, magnetic latching and unlatching functions, the level of the magnetic properties that should be available in the magnetic circuit of the new electromagnet design can be estimated. It should be noted also that, while the magnetic circuit consists of a core, an armature and a yoke or return polepiece, in order to maintain the present construction and mode of operation of the crossbar switch, the first efforts were directed to realize the design objectives with only a simple change in the material and design of the core.

The next step taken in the development of the design, therefore, was to make an analysis of the commercially available magnetic materials that might be suitable for the new magnet core design. Since the maximum contact spring loads represented by Fig. 2 are comparable to those of the present nonlatching hold magnets, the new magnet core material had to be capable of developing a level of magnetic induction strength that was not much below that of the presently used core, which is made of annealed low-carbon steel, in order to operate the electromagnet on reasonable values of magnetomotive force. The residual magnetic induction of the material, however, should be supported by a much stronger coercive force value, in order to produce and maintain the desired high level of magnetic latching force. It appeared that one type of magnetic material that should be considered was the magnet steels, which can be processed to develop (a) high flux strength at reasonably low magnetizing forces and (b) high remanence with a suitable value of coercive force. A brief analysis of the essential magnetic properties of known steels that have at least some of the desired magnetic characteristics is given below.

Table I shows a comparison of the pertinent magnetic properties of (a) annealed 0.10 per cent carbon steel, which is widely used for the magnetic circuit of many types of electromagnetic switching devices with simple operating requirements; (b) hardened 0.9 per cent carbon steel and (c) hardened 5 per cent tungsten steel, both of which were used for making permanent magnets about 50 years ago, before the development of more efficient permanent magnet alloys containing less iron and more of other alloying elements.

The 0.10 carbon steel has adequate values of magnetic permeability and saturation induction to develop the required open-polegap tractive forces. Its coercive force, however, is too low to retain the residual flux density required to produce the needed latching force. The hardened high-carbon and tungsten steels have the necessary coercive force, but their permeability is too low to develop the required values of flux densities with the available operating power. The combination of values of magnetic properties needed to develop the required tractive and latching forces, with the operating magnetizing force available in the electromagnet, will be described later.

4.1 *Selection of Magnet Core Material for Study*

It appeared, therefore, that the magnetic properties required to meet the desired operating and latching functions were in between those of the annealed low carbon steel and the hard permanent magnet type of steel. Since the magnetic properties of high carbon steels are known to vary with the hardness of the physical structure of the steel, it was conceived that a critical study of this relation, instead of the usual

TABLE I—TYPICAL DATA FOR ANNEALED LOW-CARBON MAGNET STEEL AND HARDENED HIGH-CARBON PERMANENT MAGNET STEEL

Magnetic Characteristic	Annealed 0.10 Carbon Steel	Quench-Hardened 0.9 Carbon Steel	Quench-Hardened 0.7 Carbon 5.0 Tungsten Steel
Saturation induction, B_s, in gausses	21,000	12,000	13,000
Residual induction, B_r, in gausses	10,000 to 14,000	8,500 to 10,000	8,500 to 10,300
Coercive force, H_c, in oersteds	1.8	50	70
Permeability, μ_{max}	2,000	111	123

Note: These data are representative of the magnetic properties obtained with test ring samples of the material and the magnetizing force (H_{max}) value is generally 300 or more oersteds.

study relating magnetic properties to heat-treating temperature cycles, should disclose the best combination of operating and latching magnetic properties possible with the high carbon steel. This new approach to evaluate the magnetic properties of hardenable steel was better than relying only on the measured temperatures and time of the heat-treating cycles, because the iron-carbon alloys resulting from the latter cycles usually vary considerably with the size and shape of the specimens. A laboratory study was therefore undertaken to determine the quantitative relation between the measured physical hardness produced by controlled heat treatments and the magnetic operating and latching properties, using a commercially available high-carbon steel for the magnet core test specimens.

In order to carry out the above study so that the results would be directly applicable to the magnet core design, the type of high-carbon steel selected for the study was determined on its merits from the standpoint of uniformity in composition and commercial availability in the round stock size best suited to the hold magnet design, 0.375 inch diameter. With these factors in mind, a tool steel having the nominal composition of iron plus 1.2 per cent carbon, 0.3 manganese, 0.22 silicon, 0.10 vanadium, 0.025 sulfur and phosphorous was selected. This grade of steel has been used for many years by the machine industries, primarily for making hardened tools and machine parts. Machine shop practices on the quenching and tempering of parts made from this grade of tool steel show that the parts can be hardened over a wide range of hardness values by first heating them to about 1475°F, immediately quenching in a liquid cooling medium (water or oil), then reheating at a lower temperature and slowly cooling in air at room temperature, the value of the reheating temperature being the principal determinant of the physical hardness of the parts. It should be noted, however, that the time cycles of heating and cooling, and the ambient atmospheric conditions during heating from the standpoint of minimizing decarburization, have important effects on the resulting chemical and physical changes that take place in the structure of the steel parts. The laboratory study therefore was planned with well-controlled experiments in heat treatment and the evaluation of the associated magnetic properties that control the operate, latching and unlatching functions in the electromagnet.

4.2 *Development of the Magnet Core Poleface Design*

In order to have the results of the experiments on the magnetic properties of the steel specimens directly applicable to the hold-magnet design, the size and shape of the test specimens were designed to represent an efficient magnet-core design. It is of interest, therefore, to examine the effect of the size and shape of the core poleface surface on the operating and latching characteristics of the electromagnet. The importance of the poleface design cannot be overemphasized, because the working margins obtained in the operating and latching capabilities of the magnet are largely affected by the poleface design. Some of the functional aspects of the poleface design are discussed below. In this discussion the core specimen is assumed to be a $\frac{3}{8}$-inch-diameter rod, approximately 3.5 inches in over-all length, because this is the maximum size that can be conveniently used in the present crossbar switch structure.

The following general relation between poleface area and magnetic force of attraction may be used to estimate the optimum value of the area for (a) the open polegap force and (b) the closed polegap or latching force:

$$F = \frac{\Phi^2}{8\pi A}\left(\frac{1}{980}\right)k$$

where F = the force in grams,

Φ = the magnetic flux in maxwells, between the poleface area A and the mating surface area on the armature,

A = the poleface area in square centimeters,

k = a constant, the value of which corrects for the nonperpendicularity in the direction of Φ between the mating polefaces.

Based on experience with flux measurements on this type of magnetic circuit design, the value of k is slightly less than one for the closed polegap condition. For the open polegap conditions, the greater the gap the smaller is that value.

Since the value of the polegap flux Φ is determined by the applied coil ampere-turns and the corresponding values of magnetic reluctances prevailing in the complete magnetic circuit of the electromagnet, one important portion of which is that of polegap, the general effect of poleface area A on the force F can be described by referring to the ampere-turn and reluctance form of the force equation

$$F = \frac{2\pi(\mathrm{NI})^2}{A(R_0 + R_g)^2}$$

where NI = ampere-turns,

R_0 = sum of all reluctances in the magnetic circuit except that of the polegap,

$R_g = l/\mu A$ = polegap reluctance,
l = length of the polegap,
μ = permeability of air and metal finishes in the polegap.

It can be shown, therefore, that when l is very small, as it is in the latched condition of the polegap, since R_g is then also relatively small, the value of F is made greater by using a smaller value of A up to the limit when its value results in a significant increase in the value of $R_0 + R_g$.

Conversely, when the values of l are relatively large, as they are during the operating travel of the magnet armature, the corresponding values of R_g are large enough to be controlling in their effect on the values of F. Then the value of F is made greater by increasing the area A up to the limit when its effect on the value of $(R_0 + R_g)^2$ is no longer significant.

Another important consideration in the design of the core poleface was its shape or geometry. This factor deals with the uniformity of the closed-polegap reluctance, as affected by the relative alignment of the armature poleface surface against that of the core. It is well known that two mating flat poleface surfaces usually make only a line contact and therefore result in an angular airgap. In this magnet design, a forward displacement of about 0.005 inch in the position of the core with a plane poleface would result in a separation of about 0.003 inch at the center of the core poleface. To avoid the detrimental effect of unavoidable misalignments, the poleface surface on the core was shaped like the surface of a 16-inch-diameter sphere, while the mating poleface surface on the armature was flat (commercial quality). As can be seen from the sketches in Fig. 3, the common contact area between a flat and a spherical surface is affected comparatively little when the core is displaced about 0.005 inch. Under common manufacturing conditions, therefore, the use of a large-radius spherical poleface mating with a flat poleface results in considerably less variation in the closed polegap reluctance, particularly with the type of hold magnet structure shown in Fig. 4.

This is by no means intended to represent a complete discussion of the effects of poleface area and shape on the magnetic force of attraction. It is sufficient to show, however, that the latching force is greater with a smaller poleface area at the expense of some loss in the force of attraction at the large open polegaps, and that the strength and uniformity of the latching force are better with the spherical surface.

Referring to Fig. 4, observe that the magnet core of the nonlatching design (present crossbar switches) has a poleface area much larger than the cross-sectional area of the core, the enlarged poleface being produced by an automatic cold heading operation on the soft steel rod. This poleface design was made to obtain greater efficiency in producing the open polegap tractive forces. The magnet core of the magnetic latching design (new crossbar switches for the line concentrator), however, requires a much smaller poleface area. The value of its area was determined on the basis of providing a latching force of at least 1450 grams, in order to have about 25 per cent margin above the latching force required to hold the maximum load of 1150 grams. This margin was determined by estimating the effect of vibrations and shocks on the hold magnet when the crossbar switches and associated equipment are mounted on a telephone pole. Available data on the amplitudes and frequencies of vibration that may occur on a telephone pole indicated that the resulting acceleration may be as high as 1 g at the mounting position of the crossbar switch. In view of the wide range of compliances and masses in the structural parts of the crossbar switches, the estimated margin of minimum 300 grams between the maximum load and the minimum latching force was considered a suitable temporary value, until confirmed by laboratory vibration tests.

In order to develop a minimum latching force of 1450 grams with a

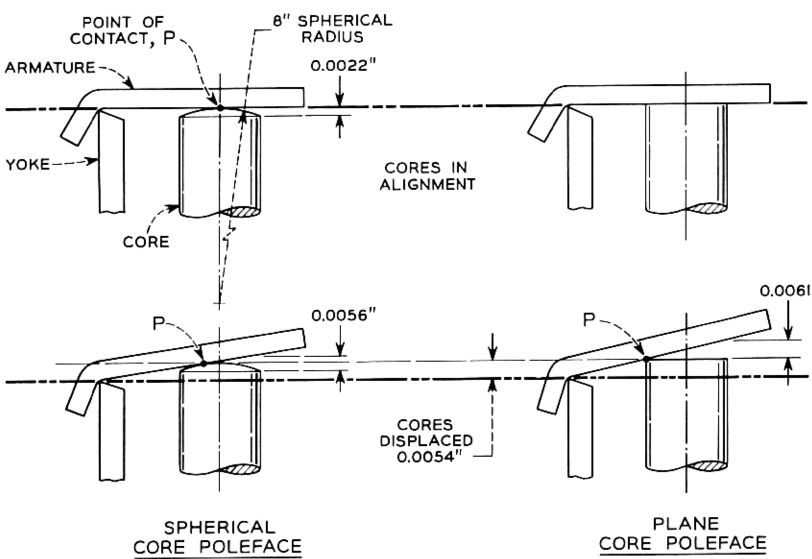

Fig. 3 — Schematic showing general effect of armature misalignment on closed-polegap reluctance.

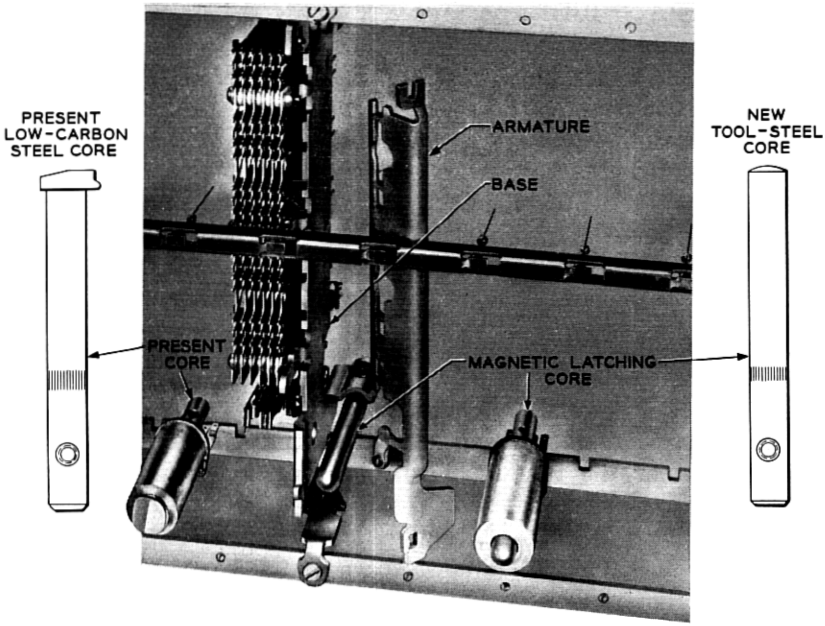

Fig. 4 — Hold magnet structure with large-radius spherical poleface mating with flat poleface.

$\frac{3}{8}$-inch-diameter magnet core, the most efficient poleface area was estimated by assuming expected values of residual magnetic induction and coercive force in the body of the prospective magnet core, under the influence of the self-demagnetizing action of the magnetic circuit. As shown by the B_r values given in Table I, it appeared reasonable to assume that the residual induction of a high quality steel core should be at least 9,000 gausses. With these assumed values of latching force and residual flux density the estimated poleface area A was obtained as follows:

In the relation

$$F = \frac{\Phi^2}{8\pi A}\left(\frac{1}{980}\right)k$$

let $F = 1650$ grams (average value) and $k = 0.85$ (estimated value).

Since the cross-sectional area of the core is 0.71 sq cm, a flux density of 9000 gausses represents 6300 maxwells in the core. Assuming a loss of 10 per cent due to core surface leakage, the value of Φ reaching the poleface is 5670 maxwells.

Therefore, $A = 0.651$ sq cm, or very nearly the same as the cross-sectional area of the core.

With regard to the importance attached to poleface design, it may be of interest to note that the mating of a spherical with a plane surface is not new with this magnetic latching design. It was first used to obtain uniformly closed polegap reluctances in the design of the Bell System's Y type (slow release) relay, in 1935, and again in the more recent design of the AG type (slow release) relay.

4.3 *Magnetomotive Force Available To Energize the Electromagnet*

After the structural size and shape of the magnetic circuit was well defined, it was necessary to determine the minimum level of operating ampere-turns that would be available in the magnet coil to develop the required magnetic properties. The need for this is apparent when it is considered that the residual magnetic properties obtained from the saturating level of magnetization are different than those obtained from apprecially lower levels.

Knowing the available winding space in the magnet coil and the electrical pulse strength in the circuit, and assuming worst circuit operating conditions under outdoor extreme temperatures of $-40°$ to $+140°$F, the steady-state value of coil ampere-turns available to energize the electromagnet was found to be a minimum of 565 and a maximum of 1065. This wide range of magnetomotive force was partly due to a circuit condition that placed two of the magnet coils in parallel and both in series with a protective lamp. These extremes of circuit operating values account for the importance attached to the minimum and maximum total load values described earlier.

V. INVESTIGATION OF MAGNETIC PROPERTIES WITH THE NEW MAGNET CORE DESIGN

The purpose of this investigation was to determine whether the selected high-carbon tool steel core could be made to yield a combination of pertinent magnetic property values when the magnet was energized with the available magnetomotive force values. The processing of the steel core, of course, was to be a reproducible hardening heat treatment. The essential experiments and test results in this investigation can now be described in relation to the desired design capabilities. Since the purpose of this study was to find the relation between the physical hardness of the steel core, as produced by hardening heat treatments, and the resulting pulse operating and latching characteristics, a practical test method was used to determine the relation, in addition to the direct measurements for magnetic characteristics of the individual steel core specimens.

5.1 *Procedure for Evaluation of Test Results*

The criterion used for the appraisal of the test results is a special form of demagnetization curve plotted in terms of the instantaneous values of magnetic latching force in grams and demagnetizing magnetomotive force in ampere-turns, as the applied saturation magnetizing force is abruptly reversed to the demagnetizing value. Each demagnetization curve represents the typical data obtained on several test cores having the same particular level of physical hardness, and each core was tested with the same hold magnet structure and coil. It should be noted that the preparation of the test-core specimens involved the establishment of uniform machining of the core poleface and uniform heat treatment processes, in order to minimize extraneous variables.

With regard to the determination of physical hardness, in order to obtain data directly applicable to subsequent manufacturing test requirements, each test core was measured on the 30-N scale of a Rockwell superficial hardness tester, before the corrosion protective finish was applied to its surface. This nondestructive and simple method of measuring hardness is one of the accepted inspection testing methods. However, since it measures hardness to a depth that is only a small fraction of the cross section, its accuracy depends upon the uniformity of the hardness throughout the volume of the test specimen. This presented no serious problem, because the small radial depth and uniform section of the core specimens assures a reasonably uniform hardness.

With regard to the Rockwell hardness numbers used to designate the physical hardness of each test specimen, it should be noted that they represent the actual 30-N scale readings as taken on the cylindrical surface of the 0.375-inch-diameter cores before the application of the protective finish. In order to reproduce the same physical hardness represented by these Rockwell hardness numbers on parts having different radii of curvature or having flat surfaces, the numerical values should be corrected according to the empirical tables furnished with the Rockwell tester. For example, in our data, the hardness readings from 54 to 64 would become 55.5 to 65 when converted to represent readings on flat surfaces.

5.2 *Magnetic Latching Forces Versus Hardness*

The characteristics of two cores of widely different degrees of hardness are shown in Fig. 5, one representing the maximum and the other

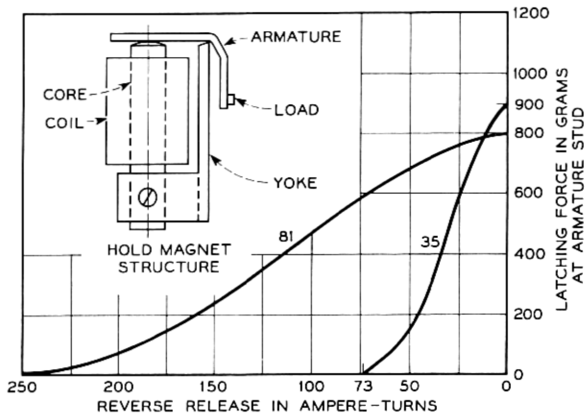

Fig. 5 — Magnetic latching characteristics of hold magnets with cores of maximum and minimum physical hardness.

the minimum hardness. Each curve is designated by the Rockwell 30-N hardness number, as measured on the cylindrical surface of the test core. The number 81 represents the maximum hardness value, as obtained after quenching and then reheating to a stress-relieving temperature of 350°F; the number 35 represents the minimum hardness value on the core, as obtained with a high-temperature (about 1600°F) normalizing heat treatment. Observe that the number 81 (hard) core developed an open circuit latching force of 800 grams, which is only 57 per cent of the required minimum value. Its demagnetizing pulse strength, however, was 250 NI, a value that is greater than desired for controlling the release of the electromagnet with the minimum load of 140 grams. In contrast to this permanent-magnet type of core, observe that the number 35 (soft) core developed a latching force of 900 grams, while its demagnetizing value was only 73 NI. It was evident, therefore, that neither of these cores representing extreme levels of physical hardness had the necessary magnetic residual induction strength. More details on their magnetic characteristics will be given later, by showing some of the actual magnetization hysteresis loops of the test-core specimens.

Fig. 6 shows the magnetic latching characteristic curves of the two cores having Rockwell hardness numbers of 72 and 41, together with the former set of curves for comparison. Observe that the number 72 hardness core developed a latching force of 1200 grams, while the number 41 core developed a latching force of 1350 grams. Compared to the slightly harder and softer cores with hardness numbers of 81 and 35, respectively, a gain of 50 per cent in latching force is realized for each

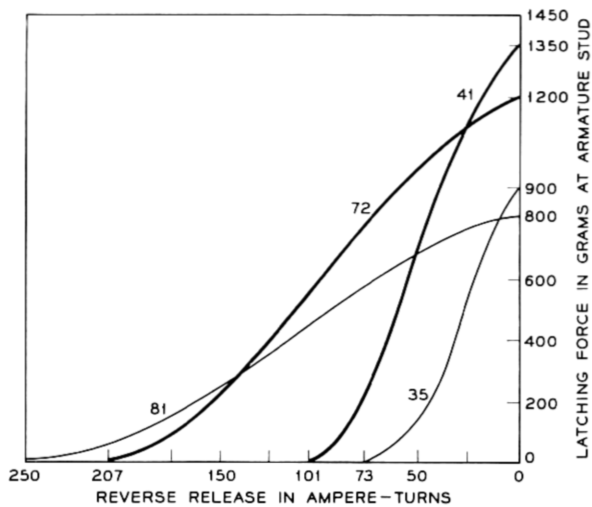

Fig. 6 — Effect of small changes in hardness of core on resulting latching force.

of the two intermediate hardness cores. Observe also that the corresponding demagnetizing ampere-turn values have changed considerably, the more important change being on the number 41 hardness core.

From the designer's viewpoint, the above results are very encouraging, in spite of the fact that the open-circuit latching force is still appreciably below the required minimum of 1450 grams. It is significant that a 50 per cent increase in latching force results from a relatively small change in physical hardness. The rate at which this improvement is made by the remainder of the intermediate hardness values is therefore of even greater interest.

Fig. 7 shows an additional set of four characteristics curves, each representing a different level of core hardness, and this completes the range of core hardness levels that was investigated. Examination of the added curves shows that the open-circuit latching force continues to increase from both ends of the hardness range, and that the optimum latching force value of 1800 grams occurs with the number 60 hardness core. The demagnetizing ampere-turn value, however, continually decreases as the hardness number decreases.

The eight magnetic latching characteristic curves in Fig. 7 show that there is an outstanding improvement in the magnetic properties of the tool steel cores when their physical hardness, as produced by hardening heat treatments, is in the Rockwell hardness range (30-N) of 54 to 64.

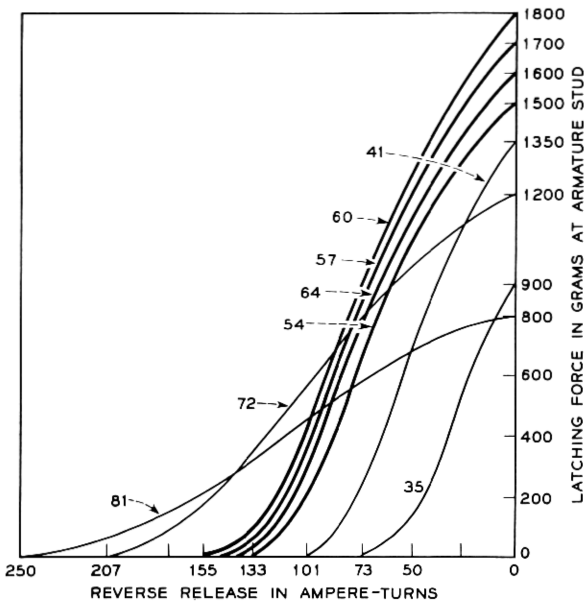

Fig. 7 — Magnetic latching characteristics of additional hold magnets with cores of different physical hardness.

The latching force values of 1500 to 1800 grams that were obtained in this hardness range provide the working margins that are necessary for the crossbar switch hold magnets. It is of interest, therefore, to examine these results from the standpoint of their reproducibility and associated variables. Also, it is desirable to examine the basic magnetic properties of the core material with these hardening heat treatments, in terms of values that can be used for other possible design applications.

The electrical operate-soak value, which determined the level of magnetic flux density established in each test core prior to the measurements for its latching force and reverse release characteristic, was kept constant at the minimum worst circuit pulse value of 565 ampere-turns. It should be noted that, with operate-soak values of greater magnetizing force, the latching characteristics are slightly different, because the resulting residual induction (B_r) values tend to be greater, while the coercive force (H_c) values are not appreciably different. The magnitude of these effects is indicated by the following test results obtained with the same test cores.

With an operate value of 960 ampere-turns, the reverse-release ampere-turn value required to reduce the latching force to zero was found to be practically the same as that obtained with the minimum operate value, thereby indicating practically no difference in H_c values. The open-circuit latching force, however, was found to be greater, up to about 10 per cent for each of the test cores with different hardness values, thereby indicating an increase of about 5 per cent in the B_r value. Since a 10 per cent difference in latching force is not a very large increase, these data show that the operate pulse value of 565 ampere-turns is sufficient to develop a substantial magnetic saturation in the test cores when the electromagnet is in the operated (closed polegap) position. The degree of saturation in the individual core, as determined by flux measurements, will be presented later.

Another important factor considered in the appraisal of the magnitude of open-circuit latching forces obtainable with this type of electromagnet design was the effect of small irregularities or foreign matter on or between the mating poleface surfaces. The magnitude of this effect is illustrated by observing the following test results.

With a given core of optimum magnetic properties (core with number 60 hardness value) assembled in a normal electromagnet, and the armature and core poleface surfaces being of good commercial smoothness and coated with a commercial nickel protective finish, the introduction of a 0.0005-inch-thick nonmagnetic separator between the mating polefaces was found to reduce the open circuit latching force by as much as 15 per cent. The reason for this effect, it can be shown, is that the added 0.0005-inch airgap increases both the flux leakage and the magnetic reluctance at the closed polegap. Since the latching force varies directly as the square of the flux value, a loss of about 7 per cent in the effective residual flux would account for a loss of about 15 per cent in force. It is obvious, therefore, that a protective finish of nickel (due to its magnetic permeability) is more desirable than a nonmagnetic zinc or cadmium finish.

5.3 *Reproducibility of Optimum Magnetic Properties*

An important factor in determining the reproducibility of magnetic latching characteristics is the sensitivity of the hardened steel core to variations from the optimum physical hardness value, during manufacture. This effect is indicated by the latching curves of Fig. 8(a). These curves are representative of the data obtained with cores in the numbers 58 to 62 Rockwell (30-N) hardness range, and with magnet assemblies having the expected range of quality in parts and alignment. The latching curves show that the physical structures in the high-carbon steel cores, as obtained by heat treatments producing Rockwell hardness

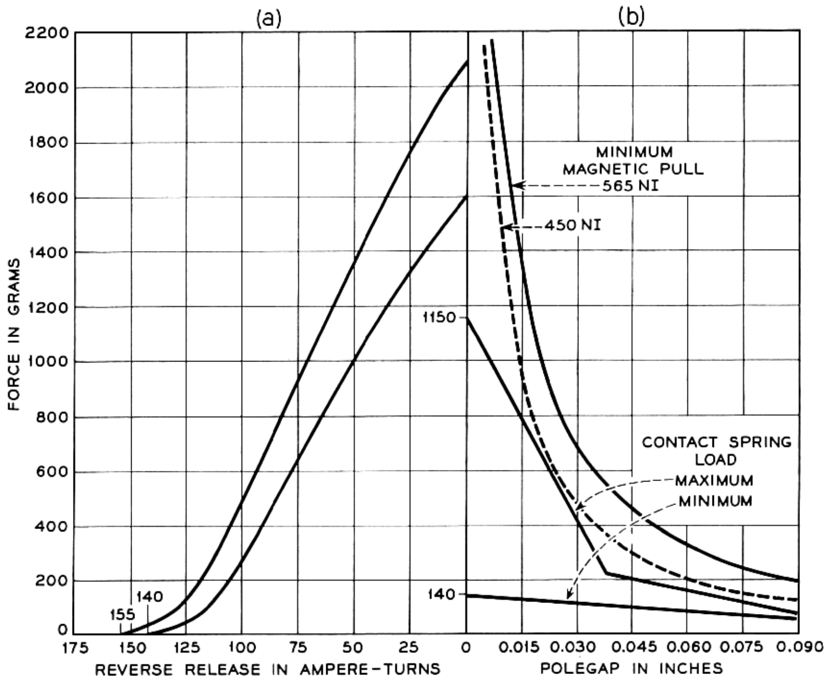

Fig. 8 — (a) Normal range of magnetic latching characteristics with 565 NI operating pulse and hardness of cores ranging from 58 to 62 (Rockwell 30-N); (b) extreme load and minimum operating pull characteristics.

readings of 58 to 62 on the 30-N scale, yield a combination of magnetic properties that provides satisfactory margins for the required magnetic latching function.

Tests were made also to determine the stability of the operating and latching properties from the standpoint of magnetic aging on the magnet cores. After about 200 hours of heating at a temperature of 100°C, no significant change due to aging could be detected.

Fig. 8(b) shows the operate pull curves for the same test parts and assemblies. The magnetic pull curve obtained with the minimum operating pulse strength of 565 NI shows that the open-gap tractive force is always considerably greater than the contact spring load, as the armature moves from the maximum-open polegap to the closed polegap position. The force differential between the load and the 565 NI pull, at each instantaneous value of polegap, determines the armature travel time. This time value, plus the time required for the current to build up to the just-operate value that starts the travel, is the maximum total operating time of the electromagnet. Since operating or switching times are of great importance, it is of interest to observe the following time data.

5.4 *Switching Times with Magnetic Latching Hold Magnet*

Fig. 9 represents a typical oscillogram of the operating-time characteristic of the magnetic latching hold magnet as it functions in a crossbar switch when load and operating power conditions are as follows: The contact spring load is the heaviest that may be encountered in the remote unit of a line concentrator; the circuit voltage is at the minimum value of 22 volts; and the circuit resistance is at the maximum value that provides the steady state value of 565 NI.

At zero time, two select magnets are energized simultaneously. At 0.030 second, the dip in the curve shows that the two associated select bars have rotated and interposed two wire fingers between the test hold magnet armature and crosspoint contacts on two separate horizontal levels. At 0.044 second, the test hold magnet is energized by the worst circuit current pulse. At 0.077 second, the test hold magnet armature has completed the switching of all contacts in the two crosspoints and in the HON spring assembly and has just reached the core poleface. At 0.122 second, the current has just reached about 95 per cent of its ultimate steady-state value.

These test values therefore show that the hold magnet operate time is a maximum of 0.033 second, and that the time required by the minimum circuit energizing pulse to build up the magnetic induction in the core

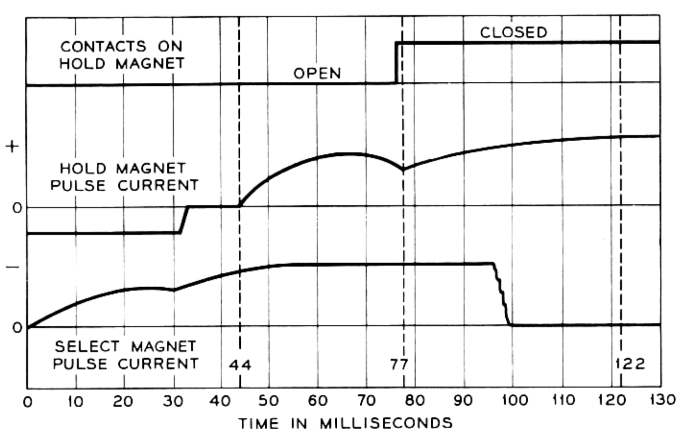

Fig. 9 — Hold magnet operating-time characteristics with minimum pulse strength.

to about 95 per cent of its steady-state value is 0.078 second. The latter time value represents a satisfactory margin, since 0.100 second was set up as the minimum time for the duration of the 22-volt energizing pulse. In this connection, it should be noted that the energizing pulse time can be reduced to much lower values by simply using higher operating voltage values to speed up the build up time of the energizing current to the same saturating value. For example, the pulse time required to obtain the same latching force capability was found to be only 0.015 second when the circuit voltage was increased to 90 volts and the ohmic resistance of the magnet circuit was increased to limit the steady-state current value to 0.200 ampere.

VI. FLUX MEASUREMENTS ON NEW MAGNET CORE

In order to observe the magnetic properties of the new magnet core material by itself, each of the core specimens representing the eight different levels of physical hardness was measured for its *B-H* magnetization characteristics. The measurements were made on a Bell Telephone Laboratories Cioffi recording flux meter system, which employs a Chattock magnetic potentiometer and an *H* integrator to measure and record the applied magnetizing force on the 3.5-inch-long test core specimen while it is being magnetized by the field between the poles of an electromagnet. The flux density *B* in the test specimen is measured and recorded directly from the test search coil on the specimen and the *B* integrator part of the system. Fig. 10 shows three of the *B-H* hysteresis loops so obtained. Each loop is designated by the hardness number of the steel core test specimen. The portion of each loop that lies in quadrants I and II represents the useful magnetic properties that determine the operate, latching and unlatching capabilities of any electromagnet using the corresponding core material, with a magnetizing force value of $H_{\max}$ equal to 143 oersteds.

The pertinent magnetic properties represented by the hysteresis loop for the (Rockwell 30-N) 60 steel in Fig. 10 are as follows:

$$B_s = 16{,}300 \text{ gausses at } H_{\max} = 143 \text{ oersteds},$$
$$B_r = 13{,}300 \text{ gausses when } H_{\max} \text{ is reduced to zero},$$
$$H_c = 24 \text{ oersteds},$$
$$\mu_{\max} = 320.$$

Referring to the typical data on magnetic properties given in Table I, it is seen that the values of the magnetic properties given above, although obtained with a much lower $H_{\max}$ value, are between those of the typical annealed low-carbon magnet steel and the hard permanent-magnet-type steels, insofar as the B_s and H_c values are concerned. The B_r value, however, is superior or at least comparable to that of the

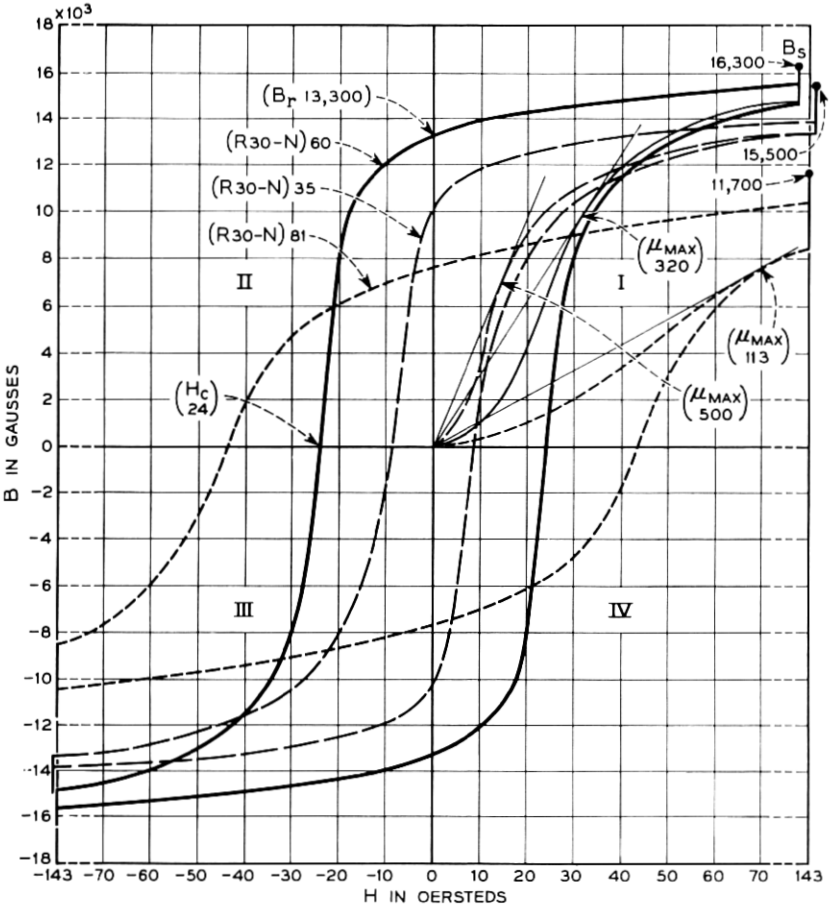

Fig. 10 — Magnetic properties of tool steel core specimens representing minimum, maximum and optimum levels of physical hardness.

annealed low-carbon steel. The fact that the B_r value is supported by an H_c value of 24 oersteds accounts for the outstanding strength and endurance of the magnetic latching force in the new design. The fact that the associated value of permeability $\mu_{\max}$ is 320 accounts for the satisfactory operating magnetic pull obtained on the minimum pulse strength.

VII. CONCLUSION

It can be concluded, therefore, that a new combination of coexisting values of magnetic properties has been found in high-carbon steel that makes it possible to use this steel as core material in the magnetic latching crossbar switch hold magnet. Four codes of such crossbar switches have been designed, and the first tool-made samples thereof have satisfactorily met all acceptance tests and laboratory life tests simulating the extreme field service conditions that may be encountered in a line concentrator.

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