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Remreed Switching Networks for No. 1 and No. 1A ESS:

Remreed Switches

By R. J. GASHLER, W. E. ARCHER, N. WASSERMAN, D. H. YANO, and R. C. ZOLNOSKI

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This paper describes a series of new two-wire matrix switches that have been developed for No. 1 ESS remreed networks. These switches utilize the new 238A sealed contact, are designed to maximize the use of automatic manufacturing techniques, and typically contain twice the number of crosspoints as conventional ferreed switches. However, as a result of increasing the crosspoint packing density, the new remreed switches consume less frame area and total volume than their ferreed counterparts.

In addition to the increase in the number of crosspoints, the new switches also contain many semiconductor devices required in the control scheme adopted for No. 1 ESS remreed networks. The extensive use of printed-wiring boards to interconnect the individual crosspoints facilitated the mounting of semiconductor components within the switch, thus yielding a natural integration of the crosspoints and the devices used to control them.

A total of seven switch codes have been developed to produce No. 1 ESS line link and trunk link networks. The manufacture of these switches has been simplified by achieving a high degree of commonality among the piece parts used to produce each code.

I. INTRODUCTION

The major apparatus development undertaken for the No. 1 ESS remreed project was the design of a series of new crosspoint switches. The goals of the new switch development were to produce designs that would be both smaller and more economical than their ferreed forerunners. These goals were met by taking advantage of the new 238A sealed contact to increase the crosspoint packing density and by designing the overall switch structure to allow for the maximum use of automatic manufacturing techniques.

The increased crosspoint packing density allowed by the 238A sealed contact is due to two factors. First, the reduced physical dimensions of the new 238A sealed contact led to a corresponding reduction in the dimensions of the new crosspoint. Second, the reduction in the amount of permanent magnetic material utilized in each crosspoint reduced the magnitude of stray magnetic fields and, hence, the total interference field felt by any crosspoint due to surrounding nearest neighbors is small. In combination, these factors resulted in an intercrosspoint spacing of 0.450 in. and led to the design of switches that contain as many as twice the number of crosspoints as conventional ferreed switches, yet consume less frame area and less total volume. This design philosophy is one key to the cost savings attributed to the remreed switch technology. The creation of switches having 128 crosspoints rather than the conventional 64 reduces the cost per crosspoint of many common manufacturing steps.

In addition to the crosspoints themselves, remreed switches also contain many semiconductor devices required in the control scheme adopted for remreed networks. The decision to include semiconductor control devices within the switch structure was made after careful consideration of their failure modes, rates, and service-affecting consequences. The printed-wiring boards inherent in the remreed switch designs made it relatively easy to mount the required semiconductor devices.

Allowing for the use of automatic manufacturing techniques was a constant constraint in the design of the basic remreed switch package. As a result, the switch design borrows heavily from the ideas incorporated in the beamless ferreed switches developed for the No. 1 ESS service link frame.[1] These concepts include the use of printed wiring boards to interconnect the crosspoint matrices, automatic insertion of the sealed contacts into their coil forms, machine termination of all control coils, and mass soldering of the final assembly. In addition, the switch designs developed were such that many existing ferreed facilities could be modified to produce the new remreed product.

II. PHYSICAL DESIGN

A total of seven remreed switch codes, generally termed the 296 types, have been developed to produce No. 1 ESS line link and trunk link networks. The 296C-1A switch shown in Fig. 1 is the workhorse code of No. 1 ESS remreed trunk link networks and, hence, will be used to illustrate general design features.

The basic construction consists of two parallel printed-circuit boards separated by approximately one inch by a series of rigid standoffs. The 238A contacts used at each crosspoint are mounted cordwood fashion between the two circuit boards. The external leads of each sealed contact fit through holes provided in the boards and are eventu-

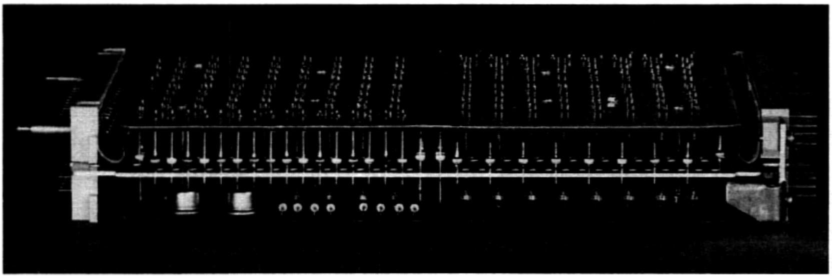

Fig. 1—296-1 type remreed switch.

ally mass soldered. The solder joints provide electrical connection to printed paths on the circuit boards and also fix the final position of each sealed contact.

Interconnecting the crosspoint arrays contained in the switch (tip-and-ring wiring) is achieved by printed paths on the two circuit boards. In addition to this tip-and-ring wiring, interconnecting the energizing coils is also accomplished via paths on the circuit boards. The tip-and-ring multiples of the crosspoint matrices are brought to terminal blocks located at the front and rear of the switch package. The input tip-and-ring leads appear at the front of the switch on terminals that are gold-plated for connector compatibility. The output leads as well as all the control leads appear on terminals at the rear of the switch. These base metal rear terminals are located on a 0.125-in. grid and have position tolerances compatible with automatic 30 AWG solderless wrap techniques.

Like the ferreed switch, each remreed crosspoint consists of two sealed contacts housed in a molded plastic coil form which is wound with the control coils used to operate and release the contacts. The basic change in the new crosspoint is the elimination of the rectangular Remendur plates used in the ferreed structure for providing the source of latching magnetic field since this function is efficiently incorporated in the reeds of the 238A sealed contacts. In principle, the remreed crosspoint functions much like the ferreed crosspoint in that both are series-magnetic structures. When the two reeds of each contact are magnetized series-aiding, the magnetomotive forces combine to produce a residual gap flux that maintains the contact closed. When the two reeds are magnetized series-opposing, the magnetomotive forces cancel and the residual gap flux is reduced to practically zero. This results in an opening of the contacts. As in the ferreed crosspoint, this latter magnetization state is produced by using pairs of unbalanced differentially wound coils; therefore, proper operation of a remreed crosspoint still requires a steel shunt plate to isolate magnetically the unbalanced coils. This steel shunt plate also serves as the mechanical backbone of the remreed switch structure.

The overall dimensions of the 296C-1A remreed switch that contains 128 crosspoints (interconnected as two 8×8 arrays) are 10.5 in. long, 5.67 in. high, and 1.59 in. wide. The volume is 80 percent of that occupied by a conventional ferreed switch containing only a single 8×8 crosspoint array. More importantly, the frontal area or frame area consumed by a remreed package is only 9 in.^{2} (5.67×1.59 in.), less than 70 percent of that occupied by a single ferreed switch.

2.1 Control coils

The coil scheme used to control an array of remreed crosspoints is identical to that used with ferreed crosspoints.[2] The crosspoints forming any row of the array are linked together with a continuous string of windings. These continuous coil strings associated with each row of crosspoints have historically been called horizontal windings. Likewise, separate continuous windings link the crosspoints that form each column of the array. The latter coil strings have historically been called vertical windings. The horizontal winding of any particular crosspoint consists of a pair of differentially wound coils; a primary coil with $2N$ turns on one side of the shunt plate connected in series to an N turn secondary coil on the opposite side of the shunt plate. The vertical winding at this crosspoint also consists of a primary and secondary coil, differentially wound and on opposite sides of the shunt plate. The full complement of coils at a remreed crosspoint, including the phase relationships, is illustrated in Fig. 2.

As a result of their differential construction, pulsing through either the vertical or horizontal winding alone magnetizes the reeds of each contact series-opposing and thus releases the crosspoint. To operate a crosspoint, a current pulse must pass through its vertical and horizontal windings simultaneously. In this situation, the primary coils on either side of the shunt plate dominate and result in magnetizing the reeds of each contact series-aiding. Remreed switches, like ferreed switches, therefore embody a destructive mark feature. A current pulse passing through a column and row of a crosspoint array operates the crosspoint at the intersection while releasing all other crosspoints along its path.

The primary coils or $2N$ coils of a remreed crosspoint have 64 turns, while the secondary or N turn coils have 31. The primary and secondary coils utilized in the ferreed design contain 39 turns and 18 turns, respectively. Increased turns were employed in the remreed design to lower the amplitude of the current pulse required to control the crosspoint to 4 A.

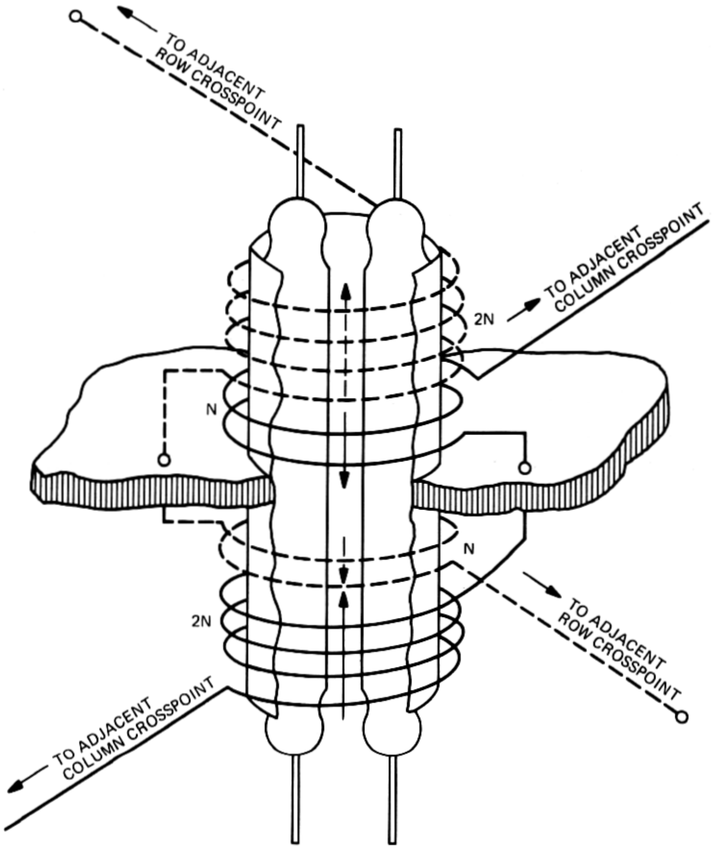

Fig. 2—Crosspoint control windings.

All the remreed control coils are wound with polyurethane-insulated 29 AWG copper wire. Given the volume available for the energizing coils, 29-gauge wire was selected as a compromise in an attempt to maximize the coil turns while minimizing coil resistance. The resistance of a complete pulse path through one row and column of an 8 × 8 array of remreed crosspoints is approximately 11 ohms. With a 4-A pulse, the peak power developed during pulsing through an 8 × 8 switch is 175 W. The peak power developed in pulsing a ferreed 8 × 8 is 250 W. However, as will be discussed later, the pulse required for remreed operation is significantly wider than the required ferreed pulse and, as a result, the total energy dissipated in pulsing a remreed 8 × 8 is greater.

2.2 Coil forms

The coil forms that house the sealed contacts and on which the control coils are wound are molded directly onto the steel shunt plate. The general shape of the coil form is illustrated in Fig. 3.

The internal configuration is hourglass in shape, providing a distinct channel or slot for each of the two sealed contacts. During coil winding, the hoop stresses produced tend to collapse the coil form and thus reduce the dimensions of the two contact channels. The wall thickness of the coil form was maximized within the space allowed for each crosspoint so that, after winding the coils, a 0.110-in. diameter gauge passes freely through each contact channel. This requirement is necessary to ensure that the sealed contacts can be automatically inserted into the coil forms.

The material selected for the coil forms is a glass-filled polyester thermoplastic, a relatively inexpensive, fire-retardant compound. As a

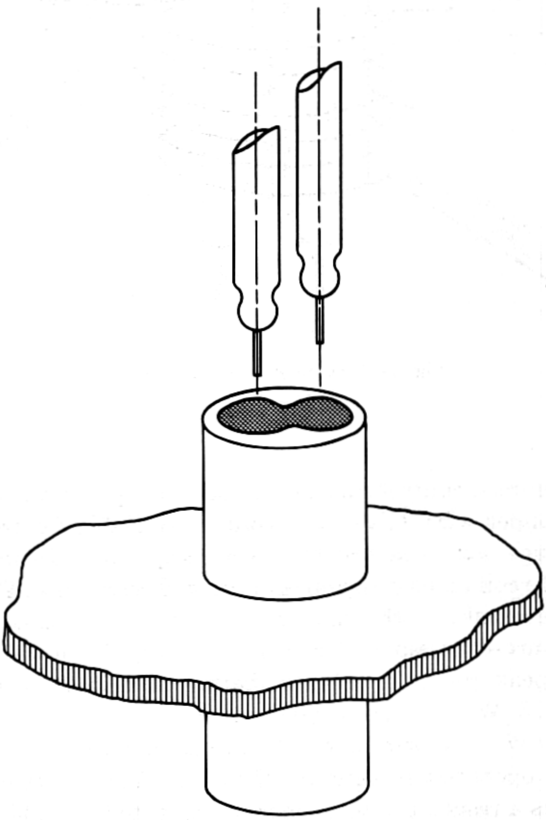

Fig. 3—Molded coil form geometry.

result of the smaller size, significantly less material is required for a remreed coil form than for a ferreed coil form. For the 128-crosspoint switch package shown in Fig. 1, all coil forms are molded in a single injection operation.

2.3 Shunt plate

Structurally, the shunt plate is the foundation around which the entire switch is built. Functionally, the shunt plate provides magnetic separation between the differentially wound coils at each crosspoint.

The shunt plate is fabricated from 0.063-in. thick low-carbon steel. Coincidentally, the amount of steel required is identical to that used in a single ferreed switch. All the openings and holes punched in the plate are referenced from a set of datum holes. These same datum holes are used for alignment throughout all subsequent switch fabrication and assembly operations. The thickness and flatness of the finished plates are closely monitored because of the dependence on these features in future coil form molding and coil winding operations.

Corrosion of the steel shunt plate is inhibited by a nickel-chrome plating applied after all punching and blanking operations are completed. A protective nickel-chrome plate was selected rather than the more standard zinc-chromate finish to avoid the whisker growth problems associated with the latter.

2.4 Printed-wiring boards

The printed-wiring boards used in remreed switches are a composite design. They consist of a conventional double-sided flexible circuit bonded to a stiff support board or support plane. There are openings or holes in the support plane corresponding to the plated-through holes in the flexible circuit member. These openings provide access to the flexible circuit for each component lead. All the semiconductor control components are mounted on the support plane side of the composite along the outside edges.

After final assembly of the switch, this edge location provides easy access to any control component in the event that replacement is required. The bonded flex composite board was selected for the remreed switch because it offers low cost as well as unique design features.

The rigid support plane to which the flexible circuit is bonded is epoxy-coated steel. The total thickness of the member is approximately 0.060 in. Epoxy-coated steel was selected as the support plane material for several reasons. First, the steel center or core of the board decreases the return path reluctance for each switch crosspoint and therefore functions as an integral magnetic member in the switch design. Second, the metallic nature of the support plane core is used to provide a ground plane in close proximity to the transmission paths on the flexible circuit and thereby improves the crosstalk performance of the switch. Last, the steel core of the support plane shields the switch crosspoint from external magnetic influences and eliminates the need for a separate steel cover as utilized in ferreed switch designs.

The flexible circuit is several inches longer than the support plane to which it is bonded. The resultant flex tongues at each end of the composite board are used to access the front and rear terminal blocks of the switch. As described in Section 2.5, accessing the terminal blocks with these flexible tongues allows the terminal block connections to be made during the final wave-soldering operation.

Bonding the flexible circuit to the support plane is accomplished with an electrical grade adhesive. Of course, in those regions corresponding to holes in the support plane, there is no bond. In these regions, the flexible circuit spans the opening much like a drumhead. The support plane opening at each crosspoint site was purposely enlarged. This places the solder joint between the sealed contact lead and the flex circuit in the center of a compliant drumhead. Thus, stresses in the final switch assembly are partially absorbed through deflections of these drumheads and, hence, the relatively fragile glass-to-metal seals of the contacts are not abused.

2.5 Terminal blocks

The basic terminal block designs used in remreed switches are quite simple. Essentially, they consist of a rectangular molded plastic block containing a field of straight-through terminals. The material selected for the bodies of all remreed switch terminal blocks is the same polyester compound used for the coil forms. Figure 4 illustrates a typical block and its interconnection to the flexible circuit tongue described in Section 2.4.

The design simplicity of the terminal blocks stems from the feature of forming the flex circuit tongue through an S-bend to carry the wiring on the flex circuit to the rear surface of the terminal block. Terminating the flex to the rear of the terminal pins is accomplished during the final wave-soldering of the switch when the block is positioned as shown in Fig. 5. Two separate blocks are used at each end of the switch. The two front blocks are rigidly mounted to the shunt plate by a set of rivets. The terminals in the front blocks are 0.025-in.^{2} pins on 0.200-in. centers and are gold-plated for connector compatibility. Two studs are provided at the front of the switch to lock on the mating female connector used in the interconnection plan adopted for remreed networks. The two rear blocks contain base metal terminals

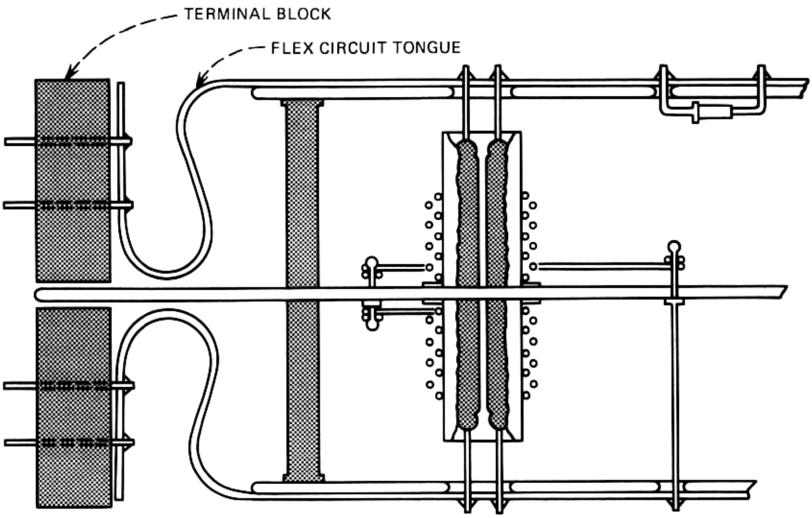

Fig. 4—Terminal block and flex circuit interconnection scheme.

spaced on 0.125-in. centers. Within each block, the position tolerance on the field of terminals is closely controlled to be compatible with automatic 30 AWG solderless wrap equipment. The rear terminals are 0.400 in. long and are secured in the plastic terminal block to withstand an axial pushout requirement compatible with solderless wrap equipment butting forces.

To guarantee proper position tolerances between the two individual terminal fields at the rear of the switch, the location of both rear blocks is adjustable. The adjustment is provided through the mounting screws used to secure the blocks to the rear of the switch.

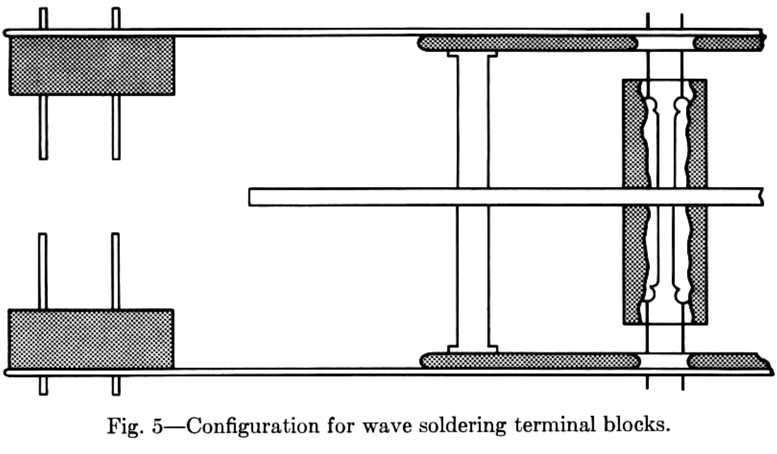

Fig. 5—Configuration for wave soldering terminal blocks.

2.6 Crosspoint spacing

The intercrosspoint spacing in a matrix switch is the principal dimension that determines the overall switch size. The intercrosspoint spacing used for remreed crosspoints is 0.450 in. The comparable dimension utilized in ferreed switch designs is 0.700 in. This reduction in crosspoint spacing allowed the development of remreed switches containing 128 crosspoints that consumed less volume than conventional 64-crosspoint ferreed switches.

The ability to mechanically space remreed crosspoints on 0.450-in. centers stems from the small diameter of the 238A sealed contact. The smaller diameter contact led to the design of a coil form with a significantly reduced cross section and this, in turn, stimulated the reduction in the intercrosspoint spacing. The factors that limited the allowable reduction to 0.450 in. were the coils required at each crosspoint and the parameters associated with the actual coil winding process. These limiting factors can be understood with the help of Fig. 6. This figure illustrates a top view of four neighboring remreed coil forms. The intercrosspoint distance, d, between these neighbors must allow enough space for the coils required on each as well as a residual aisle for the winding fingers used to lay down the coils. The rotating fingers used to wind the coils on the molded coil forms have a diameter of 0.070 in. Allowing for position tolerances and deflections of the fingers due to the wire feed tension, the residual aisle necessary for winding a field of remreed crosspoints was determined to be 0.080 in. The remaining factor to be considered is coil depth. The coil design used for remreed crosspoints has four layers (two layers for the primary coil and two layers for the secondary coil) of 29 AWG wire. The coil depth is approximately 0.040 in. Once the winding aisle and coil depth were determined, the minimum 0.450-in. intercrosspoint spacing was calculated from a diagram similar to Fig. 6.

Mechanical limitations such as coil form diameter, coil depth, and winding finger clearance requirements established a minimum crosspoint spacing of 0.450 in. for remreed switches. Subsequent to establishing the mechanical limitation, a program was initiated to study the degree of magnetic interactions between remreed crosspoints on 0.450-in. centers. This program, which showed that remreed crosspoints so spaced did not interact appreciably, is discussed in Section 3.3.

2.7 Assembly

The major assembly operations for a remreed switch are quite straightforward. First, one of the two circuit boards utilized is positioned parallel to the wound shunt plate via a series of standoffs. The sealed contacts are then automatically loaded into the coil forms. As

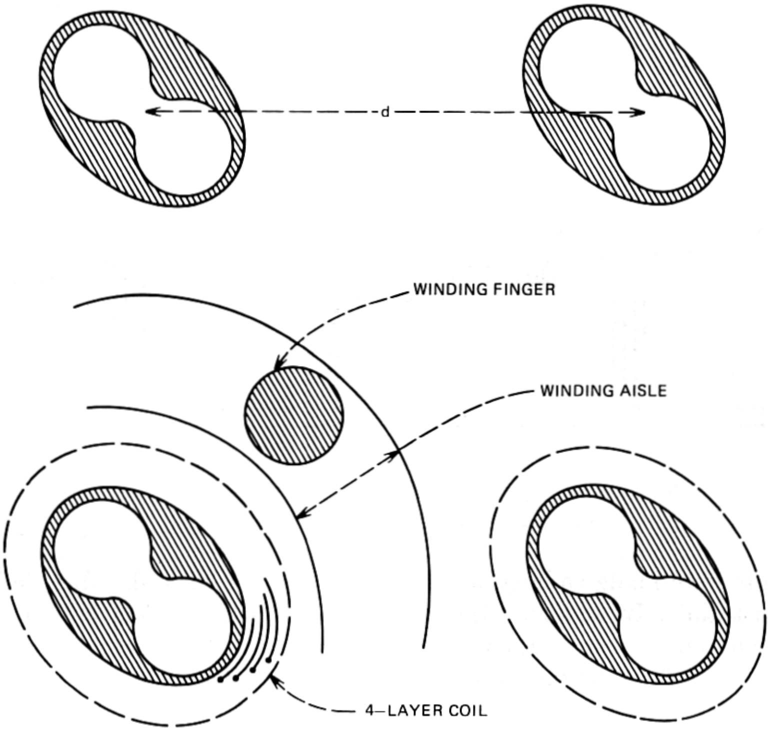

Fig. 6—Effects of coil winding on intercrosspoint spacing.

the contacts drop through the coil forms, the bottom lead of each contact enters a plated-through hole in the attached circuit board until finally the glass envelope of the contact comes to rest against the board, as shown in Fig. 7. In this position, the top leads of the sealed contacts are below the plane that will be occupied by the second circuit board. Therefore, as the second board is brought into position to complete the sandwich, only the coil feed-throughs and rivets must find holes in the circuit board. Once seated, the circuit boards and shunt plate are riveted together. Although now trapped, the contacts remain free-floating. The entire assembly is then inverted and the contacts are allowed to fall via gravity until their leads penetrate the holes in the second circuit board. Next, a magnetic fixture is used to axially center the contacts and the wave-soldering operation is performed.

Guaranteeing that the leads of each seal contact would readily enter the appropriate holes in the two circuit boards was a major design concern. To assure entry, the holes that accept the contact

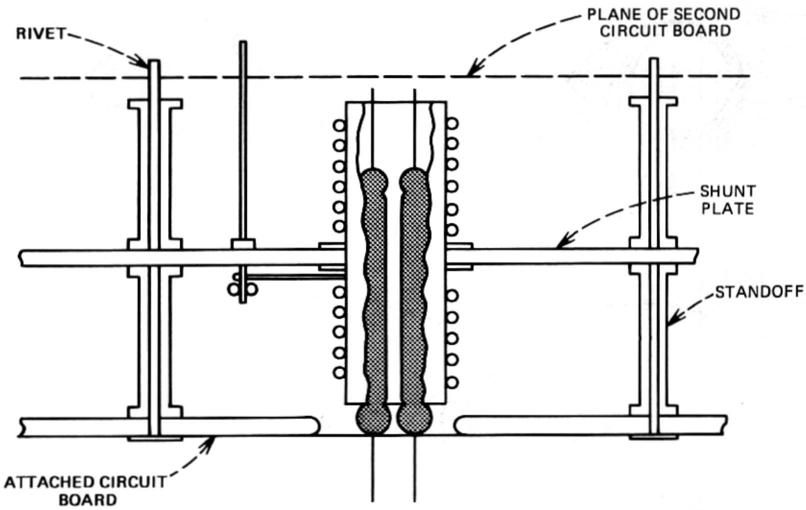

Fig. 7—Partially assembled remreed switch.

leads were made as large as possible consistent with all other design constraints. In addition, the location tolerances on each hole in the circuit board were tightly controlled. Finally, the acceptable eccentricity of 238A contact leads was constrained. These features enabled the sealed contacts to be inserted readily and not have the leads interfere with the holes in the two circuit boards.

As described in Section 2.5, the switch terminal blocks are soldered to the flex circuit tongues during the final wave-soldering operations. Subsequent to the soldering operation, the S-bends in the flex tongues are formed and the terminal blocks secured in their final positions. This type of flexible joint between the terminal blocks and the rigidly mounted support planes decouples the sealed contact leads from stresses that are applied to the ends of the switch as a result of such factors as connector insertions and wire wrap equipment.

III. OPERATING CHARACTERISTICS

The general character of a remreed crosspoint parallels in many ways that of the ferreed crosspoint. Both are pulse-operated devices that consume relatively small amounts of energy. Both are controlled with a set of differentially wound horizontal and vertical coils and employ the destructive mark feature. Both utilize Remendur as the switchable magnetic material that provides the final source of magnetic field to hold the contacts closed. Some basic differences do exist, however. These differences along with their consequences are discussed below.

The ferreed crosspoint is designed so that the residual field produced by the Remendur plates is sufficient to operate the associated 237B sealed contacts. The operation of a remreed crosspoint on the other hand is analogous to the operation of a latching relay and depends on the magnetic field of the energizing coils to actually close the 238A sealed contacts—the residual magnetism in the reeds produces only the final holding field. A second basic difference in the crosspoint designs involves the response to repetitive operate pulses. When an already operated ferreed crosspoint is given a second operate command (remarked), the net magnetic field seen by the 237B contacts is momentarily reversed. As the net field reverses direction, it passes through zero resulting in a momentary opening of the sealed contacts. This open interval occurs because the transient field produced by the energizing coils is in the direction opposite to the holding field established by the Remendur plates. Reoperating an already closed remreed crosspoint, however, results in reinforcing the residual field in the reeds of the 238A contacts. This transient reinforcing rather than reversing eliminates the open interval condition in the remreed crosspoint. The two basic differences described here had a significant impact on the characteristics of the control pulse required in remreed networks.

The current pulse developed for proper operation of a remreed crosspoint is shown in Fig. 8. Several characteristics of this current waveform deserve special attention. First, notice that the rise time or time to peak amplitude is relatively long (the entire width of the ferreed control pulse is approximately 350 μs). This long rise time primarily is to suppress rapid voltage changes during pulsing which could have a deleterious effect on the electronic control scheme adopted for remreed networks. In addition, the dependency of the 238A contacts on the coil field to produce the initial closure or pull-in also dictates a long rise time. That is, the time-to-peak amplitude must be long

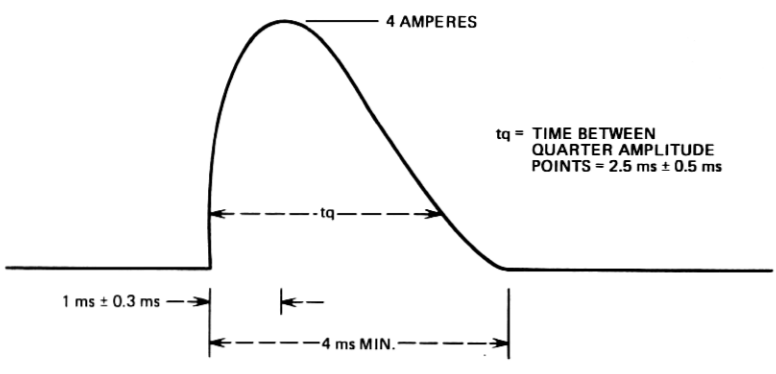

Fig. 8—Required control current profile.

compared to the operate response time of the sealed contact. Achieving initial closure prior to the peak of the pulse also guarantees the fullest level of residual magnetism in the 238A reeds since demagnetization effects resulting from any nonzero contact gap are minimized.

A second characteristic deserving special attention is the pulse amplitude. The 4-A peak current specified for controlling a remreed crosspoint can be compared to the 9-A pulse recommended for operation of a ferreed crosspoint. Reducing the control-current amplitude to the 4-A level was a requirement imposed on the remreed crosspoint design that stemmed from the decision to utilize a semiconductor scheme for steering the control pulses. Achieving the reduction in current resulted from a combination of several factors: the lower coercive force of the Remendur alloy utilized in remreed crosspoints, the smaller mean diameter of the energizing coils, the utilization of circuit support planes with magnetic cores to act as field return paths, and an increase in the number of coil turns. The first three factors are responsible for an increase in the efficiency of the remreed crosspoint. This increased efficiency results directly in a reduction of the current required to switch the magnetic material into its various configurations, thereby operating and releasing the contacts. The last factor, namely, an increase in the number of coil turns, is a tradeoff that can be made on most crosspoint or relay designs, the usual penalty being an increase in the coil impedance. In the case of the remreed crosspoint, the straightforward increase in coil turns is responsible for 65 percent of the reduction in the current amplitude. The remaining portion of the reduction is attributable to the increased efficiency of the remreed crosspoint design.

Finally, with regard to Fig. 8, note that the total pulse width specified is 4 ms minimum. The need for a longer control pulse to successfully operate the contacts in a remreed crosspoint is directly related to the fact that the residual magnetism developed in the reeds of 238A contact produces only a limited pull force, namely, that sufficient to hold the reeds closed and maintain the steady-state contact force. However, during the time immediately following initial impact of the reeds, the steady-state contact force may not be adequate to overcome the effects of reed vibration. As a result, a wide pulse is required to enhance the reed magnetization and, hence, maintain the contact force at a higher level until the violent vibrations that follow the initial impact of the reeds have appreciably subsided. If this additional pull force is not provided during the period following initial impact, the transient retractile forces associated with the various propped mode vibrations can result in a permanent reopening of the reeds. The result is a failure to operate. Even with the additional contact force provided by the sustained coil field, transient opens (contact bounce or chatter) still occur during the initial period of closure.

The long control pulse is required only for proper operation of the crosspoint. Releasing a remreed crosspoint is more straightforward and almost independent of pulse width. All that is required is to switch the magnetization direction of the two reeds in opposite directions. Pulse widths as short as several hundred microseconds are adequate to perform this switching function.

As mentioned previously, the fact that reoperating an already closed remreed crosspoint does not create a momentary open condition also had a significant impact on the control pulse used in No. 1 ESS remreed networks. When a remreed crosspoint is given a reoperate pulse, the magnetization level in each reed is momentarily increased. This transient increase in field strength is accompanied by an increase in the reed length because of the positive magnetostrictive nature of the Remendur material. This momentary increase in the length of each reed results in relative motion at the contact interfaces. This motion produces a scrubbing of the mating contact surfaces. If repeated several times, this scrubbing can result in enough cold welding of the contact surfaces that the bonds formed may not be subsequently overcome by the retractile forces available. The result is a contact that will not release. The possibility of a crosspoint receiving a series of repeated operate pulses does exist in No. 1. ESS switching networks. To avoid the possibility of generating stuck contacts due to magnetostrictive scrubbing, the control pulse for remreed networks was modified to the sequence shown in Fig. 9.

The second pulse shown in Fig. 9 is identical to that described by Fig. 8. The first or leading pulse depicted in Fig. 9 is defined as the prerelease pulse. This pulse is steered through the vertical winding of the column containing the crosspoint to be accessed and, thus, releases the crosspoint. The second pulse is then steered through both

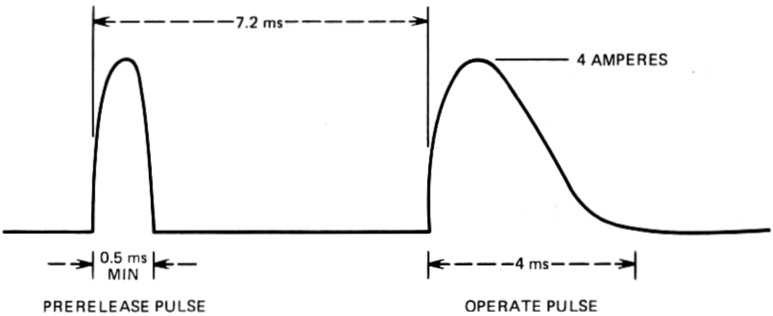

Fig. 9—Required pulse sequence for operation without scrubbing.

the vertical and horizontal windings and operates the crosspoint. Reconfiguration of the pulse path is accomplished during the 7.2-ms interval between pulses. By using this control scheme, a crosspoint that is repeatedly marked is actually released just prior to each operate pulse. In this manner, the possibility of sticking due to magnetostrictive scrubbing is avoided in remreed networks. Since the prerelease pulse is intended only to release a crosspoint, its width was reduced as shown in Fig. 9 to simplify the pulser design.

By introducing a prerelease pulse, the failure-to-operate mode discussed previously was enhanced. To understand the details of this enhancement, refer to Fig. 10. Employing a prerelease/operate pulse train created a special mode of operation known by the acronym OREO for Operate, RElease Operate. This situation is depicted by the contact state diagram included in Fig. 10 and refers to a crosspoint that is already operated and, then, is subsequently addressed by the prerelease/operate pulse train. The prerelease pulse releases the operated contacts and approximately 7 ms later the contacts are again operated. The kinetic energy of the reeds (gained as a result of being released from the initially closed state) is not damped significantly during the 7-ms interval between the prerelease and operate pulses. As a result, the operate pulse acts upon contacts whose reeds are vibrating at their natural frequencies. This reed motion can affect the ensuing closure characteristics of the contact in different ways, depending on the relative velocity and position of the reeds just prior to the initiation of the operate pulse. The effect of this initial reed motion can best be illustrated by considering several extreme situations. One extreme exists when the mismatch in natural frequencies of two reeds is such that, after approximately 7-ms of free vibration, the reeds achieve an in-phase relationship (relative velocity equal to zero at any point during their motion). This initial condition leads to closures with very little propped-mode vibrations. Instead, most of the energy gained by the reeds during closure is coupled directly into the lateral vibra-

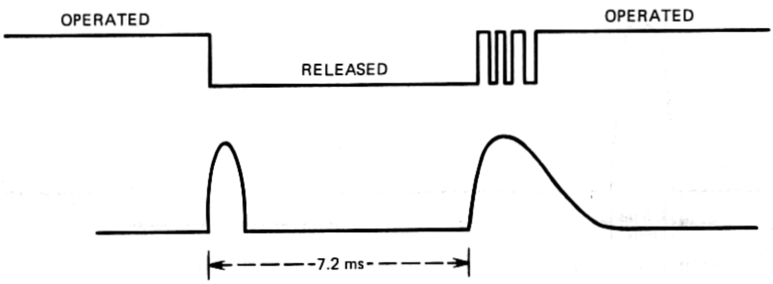

Fig. 10—Operate, release, operate sequence.

tion mode. This type of closure is not uncommon, since approximately 20 percent of the contact universe have reeds with the appropriate mismatch or beat frequency. Another limiting case exists when the natural frequencies of the two reeds are essentially identical. In this situation, after 7-ms of free vibration, the reed motion is such that the relative velocity between the reeds is periodic, alternately achieving maxima and minima. Operating a contact with reeds in this state can produce two extreme cases. The first exists when the buildup in operate field coincides with the reeds attaining a minimum separation. This condition minimizes the impact energy associated with the contact operation and results in a closure that is almost chatter- or bounce-free. The opposite of this situation exists when the buildup in operate field coincides with the reeds attaining their maximum approach velocity. In this case, the final impact velocity is maximized, resulting in extreme propped-mode vibrations. As stated previously, the effects of propped-mode vibrations following the initial impact of the reeds can lead to an operate failure if not overcome by the pull force generated during the initial closure interval.

In practice, the relative motion of the reeds just prior to the initiation of the operate pulse usually lies somewhere between the extremes just discussed. Data indicate that operating a crosspoint in the OREO sequence generally requires less current than operating a crosspoint from a quiescent release state.

Although the prerelease/operate pulse is used in every crosspoint operation in No. 1 ESS remreed networks, the OREO sequence occurs as the exception rather than the rule. In other words, most operations occur with the crosspoint initially released. In this case, the fact that a prerelease pulse precedes the actual operate pulse has no real effect on the final closure characteristics, since releasing an already released crosspoint does not produce any significant reed motion.

3.1 Operate

Remreed switches were designed to be controlled by a field pulse of 4 A. To ensure proper operation, the crosspoint developed is such that a 4-A pulse not only closes the contacts but also provides a magnetic field strength sufficient to effectively saturate the reed material. This criterion for reed saturation maximizes the steady-state contact force and, hence, yields the most stable operate condition.

The principal parameter used to evaluate the operate characteristics of the various crosspoint designs pursued during the remreed switch development was the just-operate or just-latch current value. The just-operate current for any crosspoint is defined as the minimum value of peak current required to successfully close both contacts of the crosspoint. A histogram of the just-operate currents for a typical universe of 1280 remreed crosspoints is presented in Fig. 11. These data are representative of the final crosspoint design released for production. The distribution presented in Fig. 11 shows an interval of approximately 1 A between the highest just-operate values and the 4-A field pulse requirement. This interval does not represent margin with respect to crosspoint operation, but rather the overcurrent required to guarantee that the field pulse not only operates a crosspoint but magnetically saturates the reed material as well. That is, crosspoints closed with their just-operate currents are not saturated and, as a result, do not provide a completely stable operate condition. However, the interval between the upper end of the just-operate distribution and the 4-A field pulse is utilized in practice to permit a manufacturing test pulse safely below the field requirement. The test pulse amplitude specified for the switch manufacturer is 3.6 A. Switches tested in this fashion should perform satisfactorily in the field environment even when trouble conditions may occasionally result in pulses of less than 4 A.

The effect of the OREO sequence on the just-operate current values is shown in Fig. 12. The solid curve is a repeat of the standard operate distribution shown previously in Fig. 11, while the dashed curve

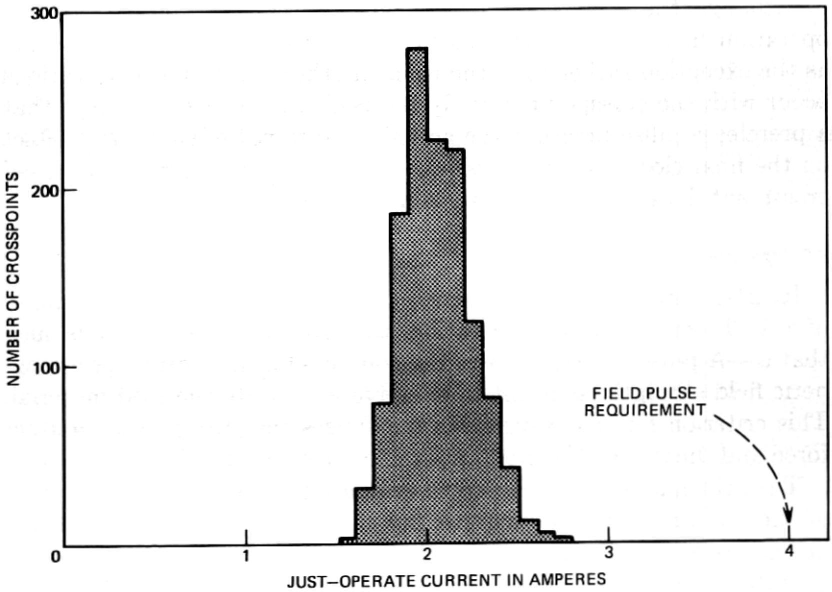

Fig. 11—Just-operate current histogram.

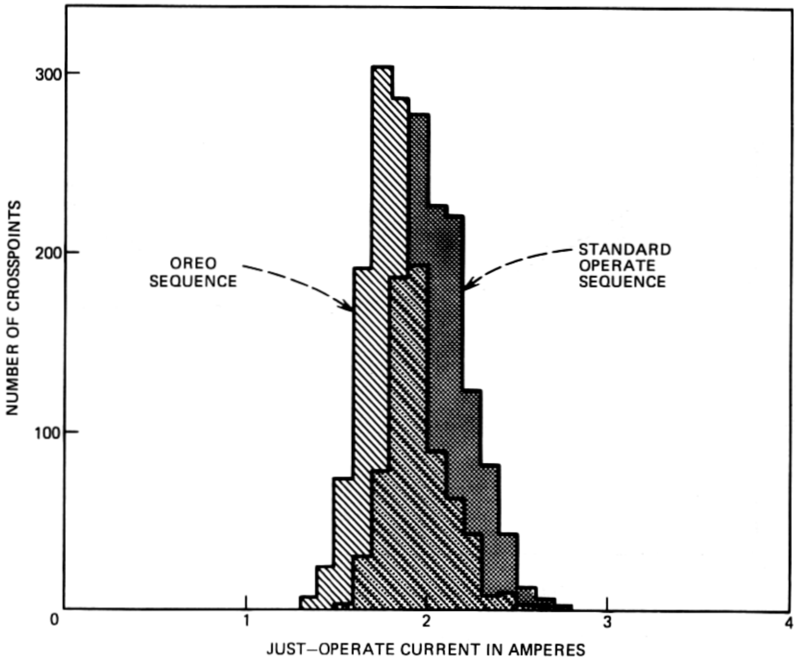

Fig. 12—Effect of OREO sequence on just-operate histogram.

represents the just-operate results for the same crosspoints when utilizing the OREO sequence.

As can be seen, the net effect of the initial reed motion developed with the OREO sequence is to reduce the average value of the just-operate current by approximately 0.2 A.

In a similar fashion to the above, the effect of various crosspoint design proposals were quantified using the just-operate current values. For example, the epoxy-coated steel planes used to support the flexible circuits were found to decrease the average just-operate current by 0.2 A when compared to various nonmagnetic support planes. This improvement results from the magnetic return paths created by the steel core.

The most important use of the just-operate current as a crosspoint design aid was in the determination of the 238A contact sensitivities which would be acceptable for remreed switches. Early in the development of the switch, it was empirically determined that the just-operate current of any particular crosspoint could be correlated with the release sensitivity of the sealed contacts used in that crosspoint. In general, the lower the release ampere turns (NI) of the contacts utilized, the higher the just-operate current. This correlation can be

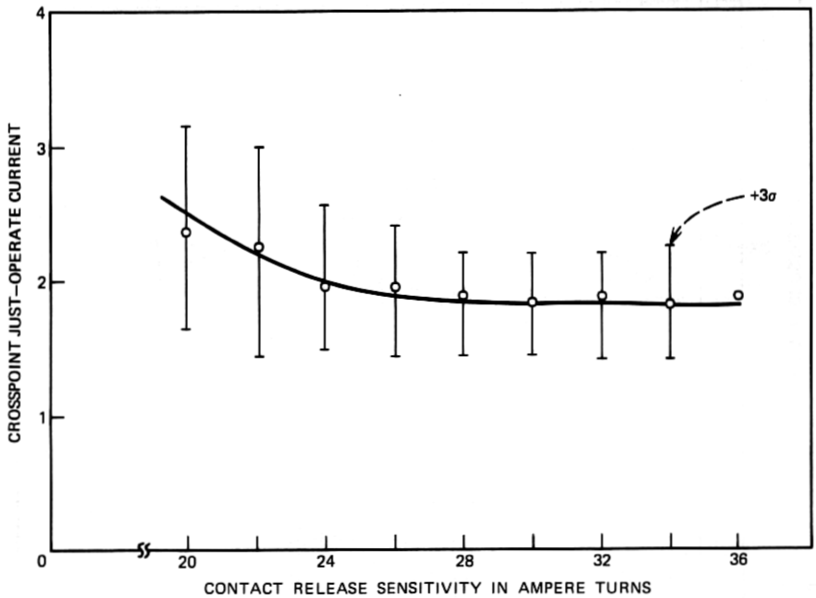

Fig. 13—Crosspoint just-operate current vs contact release sensitivity.

seen in Fig. 13. The increased just-operate currents for crosspoints having contacts with low values of NI release can be understood with the aid of the contact hysteresis loop shown in Fig. 14.

Contacts with low NI release values correspond generally to contacts with release flux levels approaching the remanent flux limit. Therefore, to operate such contacts, the field produced by the crosspoint coils has to essentially saturate the reed material since, for successful operation, the final flux developed by the reeds must exceed the release flux. A plot similar to the one shown in Fig. 13 was instrumental in selecting the 20-NI lower bound for the 238A contact-release sensitivity range.

The operate time of remreed crosspoints controlled with a pulse such as that shown in Fig. 8 is relatively fast. Data taken on many crosspoints indicate the reed bounce or chatter has ceased 3 ms after the start of the operate pulse. However, a low and stable contact resistance cannot be ensured until the ongoing reed vibrations induced by the initial impact have dampened appreciably. For this reason, the crosspoint resistance test performed by the switch manufacturer is made 50 ms after the initiation of the operate pulse.

The actual acceptance level for the terminal-to-terminal resistance test made on a remreed switch varies with the switch code. The need

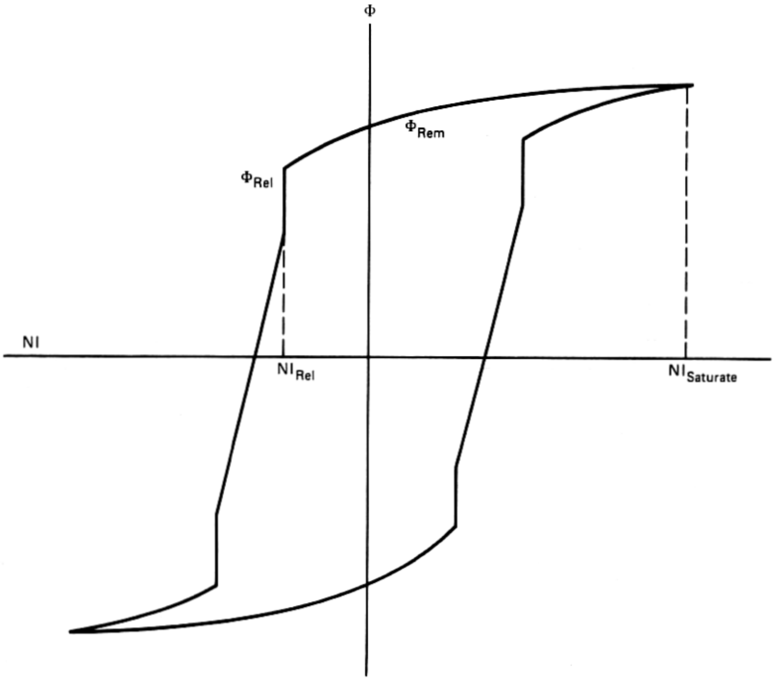

Fig. 14—Hysteresis loop for remreed contact.

for various acceptance levels is due to the difference in the length of the printed-wiring paths required to interconnect the particular configuration of crosspoints contained in each code. In general, however, the terminal-to-terminal resistance requirement applied to remreed switch tip-and-ring paths is in the several-hundred milliohm range.

3.2 Release

When any crosspoint in an array is operated, all other crosspoints in the same row and column are simultaneously released. Those in the same row are released by horizontal windings, while those in the same column are released by vertical windings. The final magnetization states that result from these two windings are shown in Fig. 15.

Any previously operated contact in the same row or column will be switched into one of the above states. In either case, only one reed of each operated contact is reversed and it is the secondary coil of the winding utilized that actually produces the magnetization reversal. The associated primary coil on the opposite side of the shunt plate merely reinforces the magnetization direction of its associated reeds.

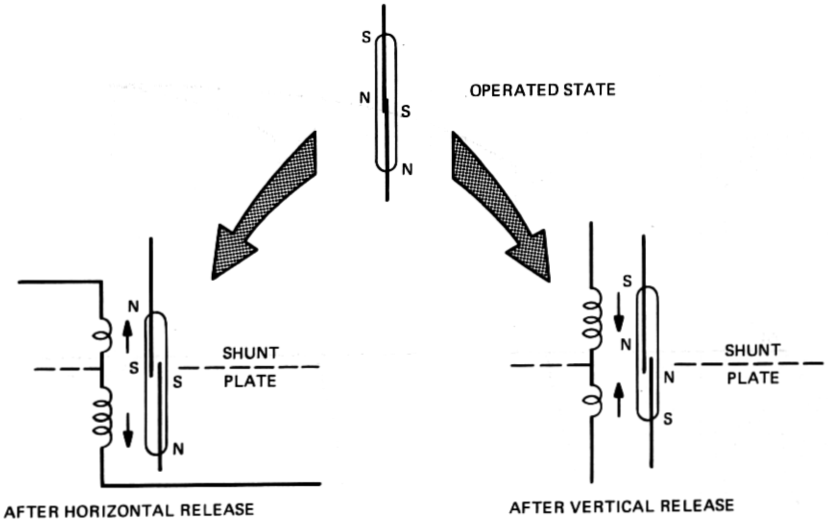

Fig. 15—Magnetic configuration of a contact after horizontal release pulse and after vertical release pulse.

This standard situation is deviated from only in the case of switching from one release state to the other, that is, from a horizontal release to a vertical release state or vice versa. In this case, the magnetization direction of both reeds is switched.

The just-release current is the minimum current pulse that will successfully release both contacts in a crosspoint from a saturate-operate state. A histogram of the just-release currents for a random universe of 1280 crosspoints is shown in Fig. 16. These data were taken using the vertical windings of the crosspoints to effect the release. The just-release current of a crosspoint depends primarily on the release sensitivity of the sealed contacts utilized at the crosspoint. The release-sensitivity range allowed for the 238A contact is from 20 to 36 NI. Contacts with release values approaching the 36 NI upper limit are the most difficult to release in a crosspoint. The distribution of contact release values is essentially gaussian, peaking at approximately 28 NI. This accounts for the relatively normal shape of the crosspoint data shown in Fig. 16.

A plot of the crosspoint just-release current versus the release sensitivity of the particular contacts utilized in the crosspoint is shown in Fig. 17, which is a partial plot in that it covers only the contact range above 33 NI. As can be seen, the higher the NI release value of the contacts, the higher the pulse amplitude needed to release the crosspoint. A plot similar to the one shown in Fig. 17 was used to

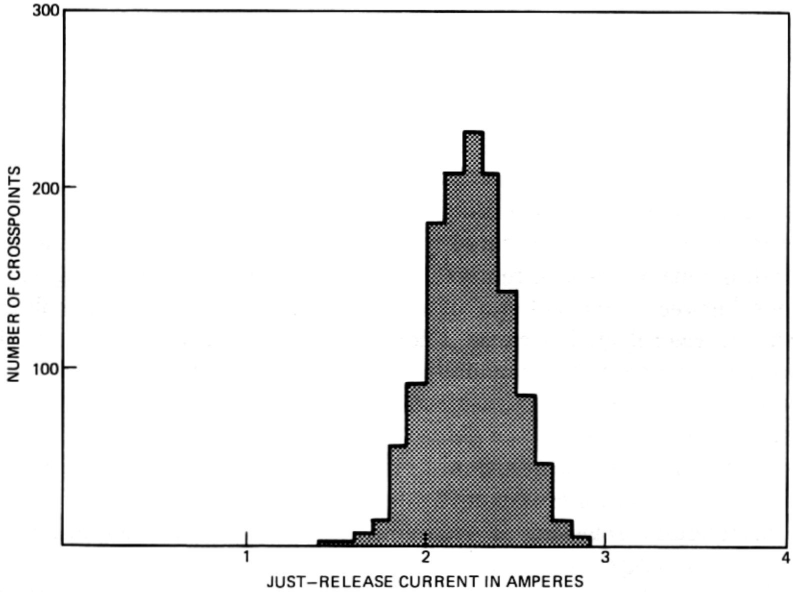

Fig. 16—Just-release current histogram.

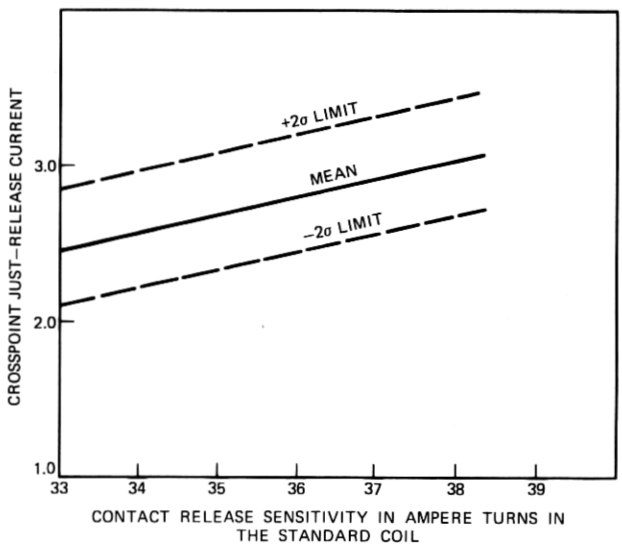

Fig. 17—Crosspoint just-release current vs contact release sensitivity.

determine the upper limit (36 NI) for the release sensitivity of the 238A sealed contacts used in remreed switches.

As stated previously, Fig. 16 gives the distribution of just-release currents for a random universe of crosspoints as measured with the vertical release windings. A similar distribution developed from readings taken with the horizontal windings shows a shift to the left of approximately 0.2 A resulting from the slightly different magnetic interference pattern generated with the horizontal windings. The coil-winding pattern used in remreed switches alternates the winding directions between each column of crosspoints. This alternating column pattern was selected because it reduces the hazard of magnetic walk-down when operating diagonally adjacent crosspoints. However, as a result, the horizontal release windings at any crosspoint are aided slightly by the interference fields of neighboring row crosspoints while the vertical release windings are opposed by the interference fields of neighboring column crosspoints.

Successfully releasing a crosspoint with either its horizontal or vertical windings can be affected by the position of the sealed contacts with respect to the central shunt plate. As stated previously, it is the N turn or secondary coil of the particular winding (horizontal or vertical) that is actually responsible for reversing the magnetization direction of one reed of each contact at a crosspoint. If the gaps of the contacts are mislocated in the direction away from the active secondary coil, releasing the crosspoint becomes more difficult. The testing requirements for remreed switches were selected to provide allowance for up to 0.020 in. of displacement of the sealed contact gap.

A second effect that can be enhanced by contact displacement is the phenomenon of momentary closure. A momentary closure is a transient closure that can occur to an already released crosspoint that receives a second or subsequent release pulse. As a result of the unbalanced primary and secondary coil system, the magnetic field of the primary coil normally dominates in the region occupied by the gaps of the sealed contacts. This is true despite the isolation intended by the shunt plate. Any displacement of the contact gap toward the primary coil aggravates this situation. Hence, when a release pulse is applied to an already released crosspoint, the transient field at the contact gap is not zero and, depending on the displacement, the gap field can be large enough to cause the contact to momentarily close. However, a lower bound of 92 NI on the operate sensitivity of the 238A contact as well as positioning requirements on the contact minimize the hazard of momentary closures. In addition, the final testing requirements on all remreed switch codes include a check for momentary closures.

3.3 Magnetic interference

Remreed crosspoints are spaced on 0.450-in. centers. As discussed in Section 2.6, this intercrosspoint spacing was the minimum allowed by various mechanical factors such as the coil design and winding limitations. To ensure the compatibility of remreed crosspoints spaced on 0.450-in. centers, all magnetic interaction effects were studied in detail.

A remreed crosspoint is not a completely closed magnetic structure. As a result, both the static and transient fields created by a particular crosspoint permeate the surrounding matrix and influence the magnetic states of nearest neighbors. The extent of this interaction between crosspoints depends primarily on the magnitude of the stray fields produced.

The stray magnetic fields produced by a remreed crosspoint are significantly less than those created by a ferreed crosspoint. The primary reasons for the reduction are the following. First, the coercive force of the Remendur alloy used in a remreed crosspoint is 30 percent less than the coercive force of the ferreed Remendur. As a result, fewer ampere turns are required to switch the material. Second, the volume of Remendur utilized at each crosspoint is significantly less in the remreed design.

The effects of magnetic interference on the performance of a remreed switch are reflected primarily in the release current and the residual contact flux. For each of the above parameters, a worst-case interference pattern maximizes the effect. Considering these worst-case interference patterns, it was experimentally determined that reductions in holding flux of about 3 percent could occur. Also, it was found that the nominal release current for a given crosspoint could be elevated approximately 0.1 A due to interference. These rather mild effects do not appreciably affect the overall switch performance.

IV. CODING

A total of seven remreed switch codes were designed to produce No. 1 ESS line link and trunk link networks. A listing of these codes and their basic crosspoint configurations is given in Table I. The seven remreed switch designs are used in combinations to manufacture four codes of larger switching units called grids. These grids, coded the 10A, 11A, 12A, and 13A, are two-stage switching units that form the basic building blocks of No. 1 ESS trunk link and line link networks. The 10A and 11A grids are used in TLNs, the 10A and 12A in 2:1 LLNs, and the 10A and 13A in 4:1 LLNs.

The use of seven distinct remreed switch codes for No. 1 ESS evolved after a detailed study of many possible alternatives for partitioning

Table I — Basic crosspoint configurations for No. 1 ESS remreed switch codes

Code	Crosspoint Configuration
296C-1A	2—8 × 8's
296C-1B	2—8 × 8's
296C-1C	2—8 × 8's
296-2A	4—8 × 4's
296-3C	4—4 × 4's plus 16 cutoff crosspoints plus 16 ferrod sensors
296-4C	1—16 × 4/8 plus 16 cutoff crosspoints plus 16 ferrod sensors
296C-5D	32 test vertical crosspoints

the larger grid units. For example, partitioning schemes resulting in switch designs having a portion of both grid stages were compared to plans that called for switches containing only crosspoints from a particular stage. Although the plan finally selected did not minimize the number of switch codes necessary, it was nevertheless accepted as a result of valuable economic input from the Western Electric Company. Their concurrence was based on the fact that the manufacture of the proposed switch codes would be simplified because of the high degree of piece part commonality achieved in the design of the seven switches.

The quantity and location of the semiconductor control components included in each of the seven switch codes varies. The components required in the switches results directly from the exact scheme adopted for partitioning each grid.

4.1 Trunk link network codes

Four remreed switch codes were developed to produce the 10A and 11A grids required in No. 1 ESS trunk link networks. They are the 296C-1A, 296C-1B, 296C-1C, and 296C-5D. These switches are used in specific combinations to form the larger two-stage grids. As shown in Table I, the 296C-1A, 296C-1B, and 296C-1C codes all contain two 8 × 8 crosspoint arrays. These codes are almost mechanically identical, utilizing the same shunt plate, printed-circuit boards, terminal blocks, etc. The differences exist in the control components included in each.

The 296C-1A is used in the input stage of both 10A and 11A grids. As such, it was designed with steering diodes in each vertical coil path. The 296C-1B is used in the output stage of 10A grids and requires steering diodes in each horizontal coil path. The 296C-1C code has diodes in both vertical and horizontal coil paths. It is used to form the output stage of 11A grids. Actually, in the case of the 296C-1B and 296C-1C, a single code (296C-1C) would have sufficed. However, the economic penalty of having superfluous diodes in the output stage of

10A grids was deemed severe enough to justify a separate 296C-1B code.

The remaining TLN code, the 296-5D, contains only 32 crosspoints. These crosspoints are controlled as four separate 1 × 8 arrays, although the tip-and-ring strapping actually forms a 1 × 32 selection. Two 296C-5D switches are utilized in the output stage of 10A grids to provide test access to each of the grid's individual output ports. As a result of the unique control scheme required in the 10A grid, over 100 steering diodes are associated with the windings of the 296C-5D switch. These devices are mounted on the 5D circuit boards and, from a design viewpoint, they offset the low crosspoint count and create a relatively dense switch package.

The 296C-5D switch was designed to use the same molded shunt plate employed in the 296C-1 type codes except that only 32 of the total of 128 coil forms are wound. In addition, the support planes, terminal blocks, and all miscellaneous hardware from the 296C-1 designs are utilized. The flexible circuit boards of the 296C-5D design are the only piece parts not common to the 296C-1 type codes.

4.2 Line link network codes

The switch codes developed specifically for the line link networks of No. 1 ESS are the 296-2A, 296-3C, and 296-4C. They are used to produce 12A and 13A grids which are 2:1 and 4:1 concentrators, respectively.

The 296-2A switch is quite similar to the 296C-1 type codes discussed in Section 4.1, except that the field of 128 crosspoints is interconnected as four 8 × 4 arrays rather than two 8 × 8 arrays. This is accomplished by way of the printed-wiring boards utilized in the 296-2A code. One 296-2A switch forms the complete output stage of both the 12A and 13A grid units.

The two other LLN codes, the 296-3C and 296-4C, are utilized to produce the input stages of 12A and 13A grids, respectively. The 296-3C and 296-4C both contain 64 crosspoints and service 16 customer lines. The 296-3C crosspoints are interconnected as four 4 × 4 arrays, and the 296-4C is interconnected as a 16 × 4/8 array. In addition to the 64 switching crosspoints, each switch also contains 16 ferrod sensors and 16 associated cutoff crosspoints for connecting and disconnecting the sensors to each of the 16 switch inputs. By including cutoff crosspoints and ferrod sensors together with an appropriate portion of the input stage of switching and interconnecting them via the switch circuit boards, a significant amount of external frame wiring was eliminated.

The ability to design functional line packages such as the 296-3C and 296-4C codes was made possible by the development of the minia-

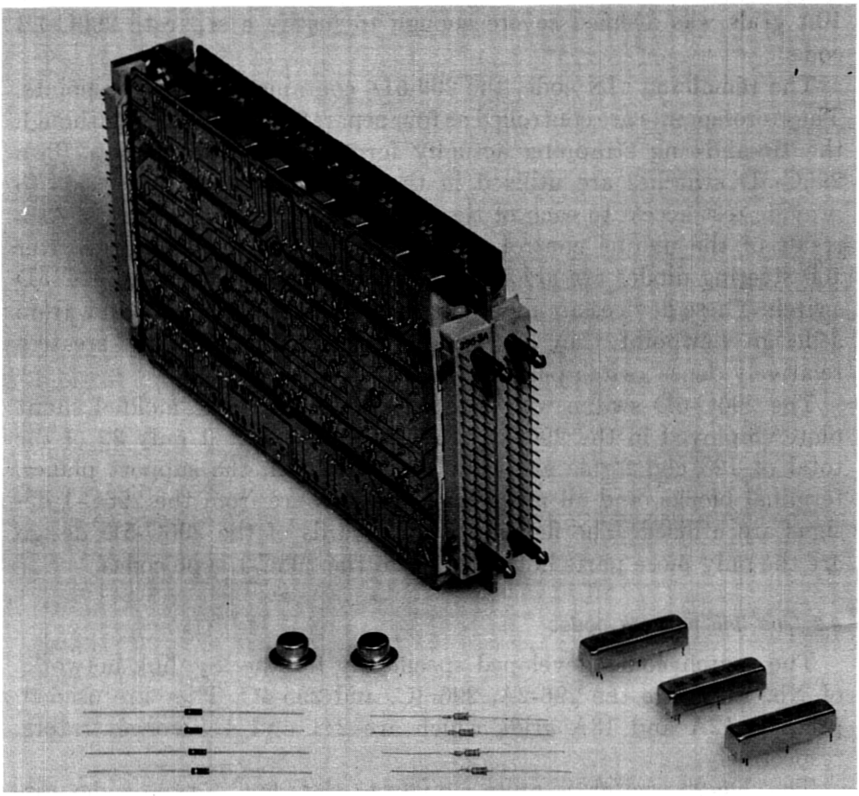

Fig. 18—296-3 type remreed switch.

ture 2A ferrod sensor. This new ferrod design is electrically equivalent to the 1B ferrod used in ferreed LLNs; however, it is a factor of 6 smaller and designed for mounting on a printed-wiring board. The 2A ferrod makes use of many manufacturing techniques common to reed relay devices, employs the identical ferrite stick piece partly utilized in the older conventional designs, and has a significantly lower cost. The RC contact protection networks required for each sensor and cutoff crosspoint combination are separately mounted on the switch printed-wiring boards. Figure 18 is a photograph of a 296-3C switch. Eight of the included sensors are partially visible along the top edge of the near printed-wiring board. Several loose sensors are shown in the lower right-hand corner of the photograph.

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