Solderless Wrapped Connections

PART I — STRUCTURE AND TOOLS

By R. F. MALLINA

(Manuscript received February 17, 1953)

In the search for a better way of connecting wires to apparatus terminals a new joining method has been discovered. The new method not only eliminates soldering and its hazards but also reduces cost, improves quality and conserves space. In contrast to the solder joint which depends largely on human judgement and skill, the new connection is made with a calibrated tool. A degree of uniformity has been obtained which virtually eliminates the need for product inspection. The trend toward smaller apparatus and automation may now be further intensified due to the use of this new method of making electrical connections.

INTRODUCTION

Methods of joining wires to apparatus terminals for the purpose of electrical conduction can be broadly divided into two groups: solder connections and pressure connections. There are others such as welded and brazed connections; however, they are relatively few in number. The annual production of solder connections in the Bell System is estimated to be one billion. In television and radio manufacture the number of connections made per year is in the order of ten billion. Because of the high cost of manual soldering, the pressure connection is of great importance to the communication industry. One form of pressure connection — the solderless wrapped connection — will be described in this article.

In order to determine the technical and economic value of a new type of pressure connection it is necessary to compare it with those now accepted as good connections in the communication industry. A large portion of this article will, therefore, be devoted to the analysis of pressure connections some of which have been in use since the early development of the telephone.

WHAT IS A PRESSURE CONNECTION?

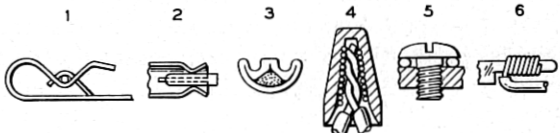
The chart Fig. 1 shows six typical pressure connections classified in terms of seven requirements. In this classification the screw connection, for example, meets the following requirements: large contact area, high contact force, great mechanical stability, long life, easy to disconnect. The space, however, which the screw connection occupies is large and its cost is high. In the history of electricity it is probably the oldest and best pressure connection. In the second column of the table in Fig. 1 is the plug connection. It is small in size, easy to disconnect, but has no large contact area, no high contact force, no long life, no mechanical stability and is not low in cost.

As will be shown later the solderless wrapped connection in Column 6 of Fig. 1 is indicated as meeting all seven requirements. Its main advantage over the screw connection is that it is low in cost and small in size.

CONTACT AREA

The effective contact area relative to the cross sectional area of the wire is of great importance since it controls the resistance of the connection. It must remain uniform in size, metallically bright and not be affected by temperature changes, vibration and handling.

Contact area is not easily defined. For example two flat metal surfaces having an area of one square centimeter each and brought into contact do not necessarily have a contact area of one square centimeter. If the force holding them together is small, only the high spots



REQUIREMENTS	1 FAHNESTOCK CLIP	2 PLUG	3 CRIMP	4 WIRE NUT	5 SCREW	6 SOLDERLESS WRAPPED
1. LARGE CONTACT AREA			✓	✓	✓	✓
2. HIGH CONTACT FORCE			✓	✓	✓	✓
3. LONG LIFE			✓	✓	✓	✓
4. SMALL SIZE		✓	✓			✓
5. MECHANICALLY STABLE			✓		✓	✓
6. EASILY DISCONNECTED	✓	✓		✓	✓	✓
7. LOW COST						✓

Fig. 1 — Classification of pressure connections.

of the surfaces touch and large currents passing through such a connection may develop heat and melt the metal at the high spots.

CONTACT FORCE

To make the above mentioned area of one square centimeter effective for electrical conduction it is necessary to press the two metal parts together with a force so high that essentially all particles of the area are intimately interlocked and free from insulating impurities. If the pressure is high enough, the film which appears in the form of oxide on the terminal surface is crushed. In general it is assumed that in a good connection the contact force should be such that the contact area produced is equal to or greater than the cross sectional area of the wire. In screw connections, crimped connections and wrapped connections the contact area is normally a multiple of the wire cross sectional area. In plug connections, such as on vacuum tube sockets, the contact area is very small. In a Fahnestock clip for example, the contact area is about one quarter of the cross sectional area of the wire.

LIFE

If the electrical resistance of a pressure joint is to remain constant with time, it is the contact area which must remain substantially constant, but not necessarily the contact force. Once the metal particles are tightly interlocked a subsequent reduction in contact force within relatively wide limits does not change the electrical resistance. The resistance will increase only when the force is reduced to such a low value that vibration and handling cause partial separation of the contact area. In such a case two changes may take place:

1. The atmosphere may enter through the fringe of the contact area and a process of corrosion may begin.

2. The effective contact area may be reduced through dislodging some of the contacting particles.

In both cases the resistance is increased. Therefore, to produce a durable connection it is important to have a firm joint and one such that the atmosphere cannot enter the contact area. The term commonly used for such a joint is "gas tight."

ELASTIC RESERVE

The question now arises how much reduction in contact force can be tolerated before a joint loses its gas tightness? In all types of pressure

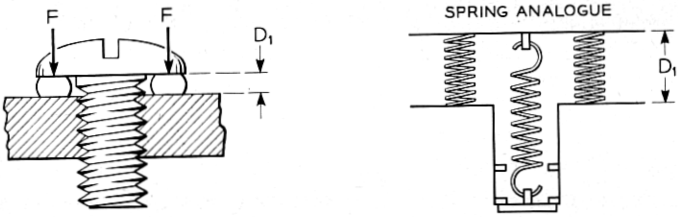


Fig. 2 — Screw tightened and wire compressed (with accompanying "Spring Analogue").

connections, the forces which hold the wire and terminal together are provided by the springiness or elasticity of the materials. The elasticity in a Fahnestock clip is quite apparent because of the long spring member. On the other hand, a screw connection, such as shown in Fig. 2, does not appear to have spring members of any kind. Analysis, however, shows that there is considerable elastic deformation. Most of this elastic deformation is in the elongation of the screw shank and there is also some bending in the screw head and some compression in the screw threads. When the screw is tightened, the wire which is interposed between screw head and nut is also elastically deformed. Since in most electrical connections the wire is a soft material such as copper or aluminum, it is nearly always compressed beyond the yield point and only the recovery of the overstressed material can be considered as elastic reserve.

To determine the usefulness of a connection and compare pressure connections of different kinds, the elastic reserve in the deformed wire and the deformed terminal must be measured or computed. Elastic reserve might be expressed either in terms of stiffness or the potential energy stored in the system. Stiffness S is defined as the ratio of the "applied force F to the elastic return D"; potential or elastic energy E is "one half of the product of the force F and the elastic return D." ($E = \frac{1}{2}FD$.)

Example: A wire is placed under a screw (Fig. 2) and compressed by the screw head to a thickness D_1. The screw is then loosened so that it just touches the wire. The wire now has expanded to a certain extent and its new thickness is D_2. (Fig. 3.) The difference ($D_2 - D_1 = D_W$) is the elastic return and the ratio $F/D_W = S_W$ is the useful stiffness of the wire.

A preferred way of expressing elastic reserve is in terms of stored energy. (Strictly speaking the equation $E = \frac{1}{2}FD$ holds only for springs with constant stiffness. A round wire compressed by a screw head becomes stiffer as the compression increases). The distance, $D_S = D_3 - D_W$, is the elongation of the screw (see Fig. 3). The total energy stored up is therefore the sum of the energy in the screw and wire ($E = E_S + E_W$).

Screws in terminal blocks are normally made of hard materials such as brass or phosphor bronze. Wires used for the interconnection of components are nearly always of a soft material and have a tendency to creep. If creep takes place in the wire during the many years a screw connection is in use, it is advantageous to have the loss of potential energy in the wire compensated for by the energy stored in the screw.

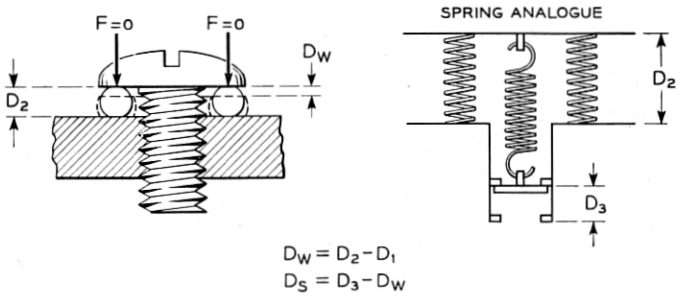


Fig. 3 — Screw loosened and wire not compressed. The recovery of the wire is denoted D_w. The recovery of the screw is $D_3 - D_w$ (with accompanying "Spring Analogue").

A screw, for example, made of soft copper would not be expected to make a lasting connection. If on the other hand the screw is made of a material which has little creep and much elasticity, such as brass or steel, it would act as a spring member and tend to keep the connection tight.

Several typical screw connections were measured to determine the elastic reserve. It was found that on an average the potential energy stored in the screw is about equal to that stored in the wire. Plastic flow of the wire creates an effective bearing area comparable to the area of the screw shank.

THE SOLDERLESS WRAPPED CONNECTION

The detailed analysis of the screw connection as an introduction to the solderless wrapped connection was necessary not only because the screw has such wide use as an electrical pressure connection but chiefly because of its proven value as a durable connection. When new types of pressure connections are put into large scale production, the question invariably arises, What is their life? While considerable analytical work has been done on the cold flow of metals under stress* and while certain

* See Part II.

theoretical predictions can be made on the durability of new connections, it affords additional satisfaction to be able to show that the solderless wrapped connection is in many respects similar in structure and performance to the conventional screw connection. If then this fact is supported by parallel analytical work, there should be little doubt that the solderless wrapped connection is a durable pressure connection.

THE RECTANGULAR TERMINAL

Generally speaking the terminal best suited for a wrapped connection is a terminal of rectangular cross section. It is an inexpensive terminal since it can be blanked from sheet stock or coined from round wire. It is ideally suited for a pressure connection because the edges produce a concentrated high pressure on the wire. The stress distribution in the wire produced by the terminal edges is shown diagrammatically in Figs. 4 and 5. If the wire is wound with high tension around the rectangular terminal, the terminal edges dig into the soft copper wire, crush and shear the oxide on both the wire and the terminal and form a large, intimate and metallically clean "gas tight" contact area. An indication of the high pressure is the crushing of the hard nickel silver terminal edge by the soft copper wire. A pattern of contact areas on both wire and terminal is shown in Fig. 6. Several turns of wire are required to preserve the high contact force. In general it is assumed that the first and last two edges around which the wire is wrapped do not contribute much to the joint as contact areas. A seven-turn wrapped connection on a rectangular terminal thus has six effective turns. Each turn contacts four edges or a total of twenty-four contact areas for six effective turns.

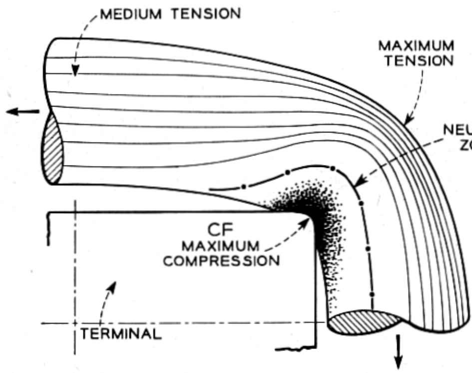


FIG. 4 — Stress distribution along one-quarter turn of wire.

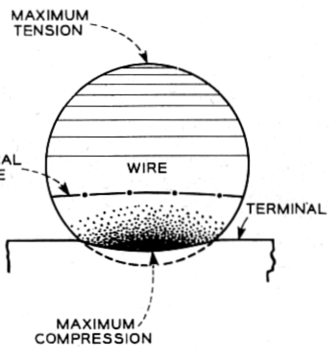
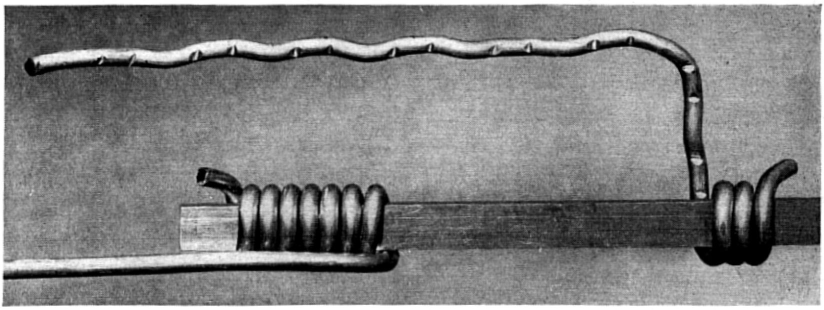
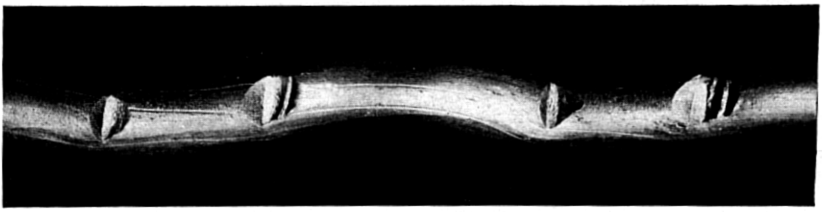


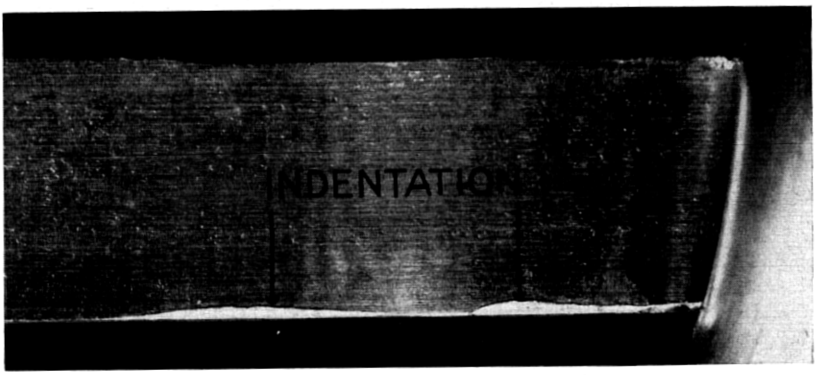
FIG. 5 — Cross section through terminal edge showing stress distribution in the wire.



Pattern of Contact Areas.



Contact Areas Enlarged.



The Soft Copper Wire Crushes the Hard Nickel Silver Terminal Edge in the Wrapping Process.

Fig. 6 — Contact areas.

WHAT IS A GOOD CONNECTION?

The quality of a connection depends fundamentally on two factors: the contact area and the contact pressure. As long as there is sufficient pressure and the atmosphere cannot enter the joint, the connection is considered a good one. If, however, the elastic energy which holds the two surfaces together is small, various disturbances may cause a partial separation of the interlocking metal particles and thus effect a change in resistance. For normal telephone applications a good connection may, therefore, be defined as one which not only has sufficient contact area and contact pressure but which also has sufficient elastic reserve to maintain contact area and contact pressure throughout the desired life, which may be forty years or more.

The mechanical disturbances to which a connection may be subjected are: handling, vibration, temperature changes and cold flow.

HANDLING AND VIBRATION

The solderless wrapped connection is well protected from the point of view of handling and vibration. The locking effect on the rectangular terminal or a terminal having well defined edges does not permit loosening of the center turns from the terminal. In vibration tests where conventional soldered connections were compared with solderless wrapped connections, it was found that solderless wrapped connections outlast soldered connections. This is due to the fact that a sudden change in cross section from wire to solder lump localizes the stresses at a very small area. (See Figs. 7 and 8.) In the screw connection a similar condition exists where the wire emerges from under the screw head. In the

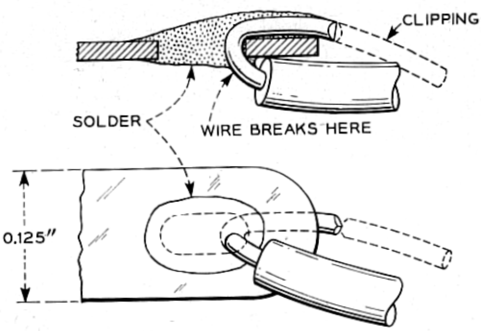


FIG. 7 — Standard solder connection of U-relay.

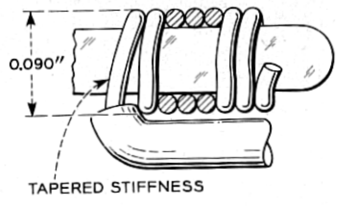


FIG. 8 — Solderless wrapped connection of modified U-relay terminal.

solderless wrapped connection there is no sudden change in cross section and therefore no localization of stresses. The term commonly used to indicate the gradual change in rigidity of the wire as it approaches the anchoring point is "tapered stiffness." (See Fig. 8.)

HEAT AND COLD FLOW

When a pressure connection is subjected to high temperatures, which may be due to large current or to heat transfer from adjacent components, the pressure at the joint is relaxed. This is true in the solderless wrapped connection as well as in the screw connection. The same process of relaxation takes place in normal temperature with time. The relaxation of pressure with temperature and time will be shown in another part of this paper. Under ordinary conditions the relaxation of pressure in a solderless wrapped connection is not sufficiently large to indicate any change in resistance during a forty-year life. Furthermore, as Mason and Osmer point out in their paper, solid state diffusion takes place as time goes on. This process strengthens the joint mechanically and improves it electrically.

QUANTITATIVE EVALUATION OF ELASTIC RESERVE

Because of the above mentioned disturbances to which a pressure connection may be subjected, it is important to know how much elastic reserve is stored in a connection. If no potential energy were stored in the wire and in the terminal, no contact pressure would be produced. If little potential energy were stored in a connection, a slight change in temperature due to differential expansion of the metals would loosen the connection. The same would be true with vibration and handling.

A rough comparison with other pressure connections will serve to illustrate how much elastic reserve a solderless wrapped connection has to have in order to withstand the disturbances to which it may be subjected. The best known pressure connection, and the most universally used, is the screw connection. On a No. 4 screw (0.112″), the force exerted in clamping the No. 24 gauge (0.020″) wire is about 135 lbs. The elastic energy is stored by compressing the wire and by elongating the screw shank. Similarly, in a solderless wrapped connection as shown in Fig. 9 a total force of 90 lbs is exerted on the edges of the terminal (24 corners). Here the greater part of the energy is stored in the terminal which receives torsional as well as compressional stress from the tension in the wrapped wire. (See Figs. 10(a) and 10(b)).

Fig. 9 shows in diagrammatic form how the stored energy in a screw connection and a solderless wrapped connection compare. A typical solderless wrapped connection — seven turns of 20-mil copper wire wound with 1300 grams applied force on a 0.0148″ x 0.062″ nickel silver terminal — has approximately 3 mil pounds of stored energy E. (2.4 mil pounds are stored in the terminal and 0.6 mil pounds in the wire). The screw connection — No. 4-40 screw (0.112″) tensioned to 135 lbs on 20-mil copper wire — has approximately 2.7 mil pounds of stored energy E. (Approximately half in the screw and half in the wire). In the screw connection the energy is about equally divided between the screw and the wire whereas in the solderless wrapped connection a larger part of the energy is stored in the terminal. This is advantageous since the hard materials of which terminals are generally made have less cold flow than copper. In a solderless wrapped connection, if the

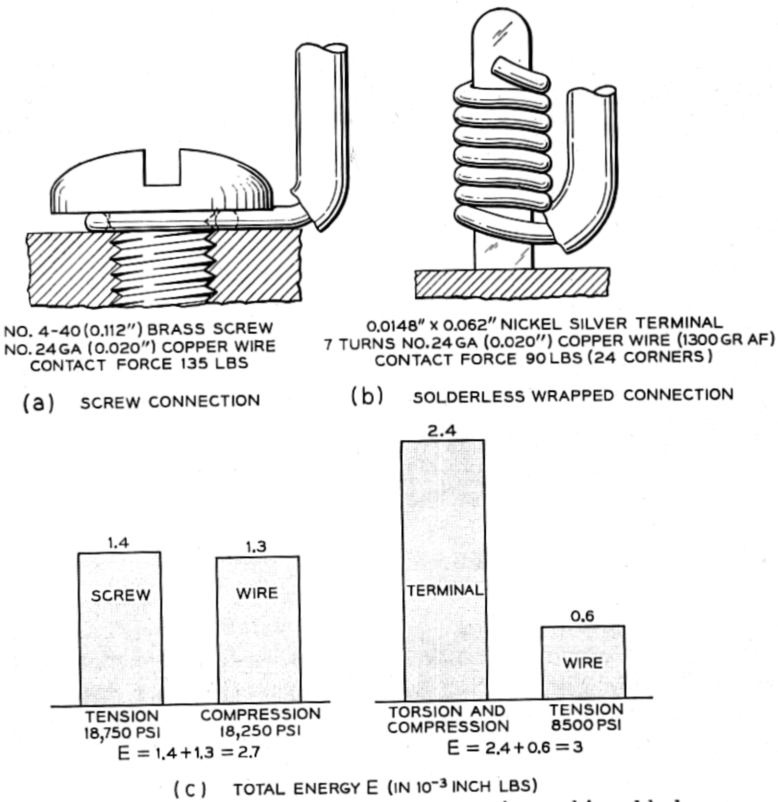


Fig. 9 — Elastic energy stored in screw connection and in solderless wrapped connection.

terminal size is changed to 0.020″ x 0.062″ there is considerably less energy stored in the terminal and slightly more in the wire. Inasmuch as a screw connection in most cases depends on the human element, that is the amount of torque applied by the operator, it can be expected that some screw connections will be made with a force that may vary from 75 lbs to 150 lbs. The wrapped connection on the other hand, being made with a calibrated tool, can be expected to give substantially the same contact force at all times.

In order to understand more clearly how the wire and the terminal interact when they are under mutual stress and exposed to heat, the elastic deformation of the wire and the terminal must be analyzed. It has been shown in Fig. 4 that the wrapped wire on the four sides of the rectangle is under tension. This tension causes the terminal to twist. If instead of a helix the terminal were surrounded by a series of hoops,

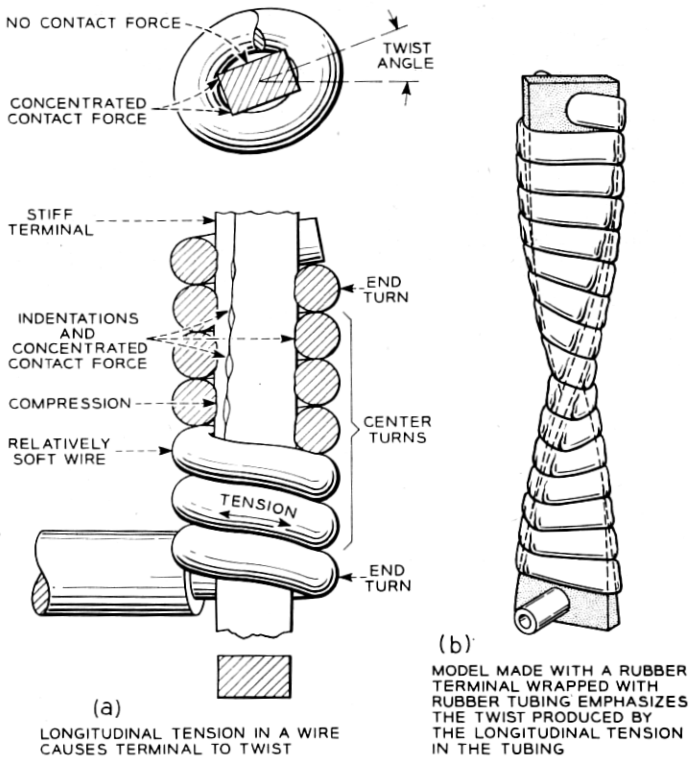


Fig. 10 — (a) Longitudinal tension in wire causes terminal to twist. (b) Model made with a rubber terminal wrapped with rubber tubing emphasizes the twist produced by the longitudinal tension in the tubing.

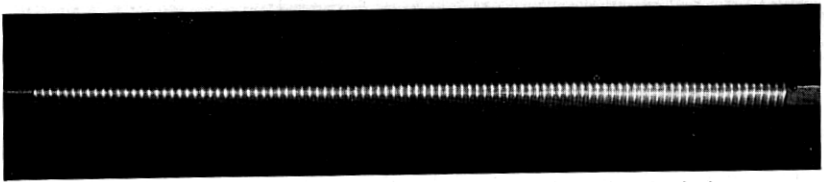


Fig. 11 — Twist of rectangular terminal (100 turns of wire).

the terminal would be compressed at the edges but the terminal would not twist. The terminal twist in the wrapped connection is therefore due to the fact that the terminal is surrounded by a helix and not by hoops. Figs. 10(a) and 10(b) show that a left-hand helix produces a right-hand twist in the terminal. As will be shown later, this visible deformation of the terminal is being used to determine the tension in the wire. The twist in the terminal of a wrapped connection with many turns can readily be seen in Fig. 11. For example an initial twist of 46° is produced in a nickel silver terminal 0.0148″ × 0.062″ wrapped with 100 turns of No. 24 (0.020″ dia.) copper wire with an applied force of 1300 grams.

One way to visualize the behavior of the wire and the terminal when wrapped under tension, exposed to time and heat and then unwrapped, is to represent the wire and the terminal by linear springs. This is shown schematically in Fig. 12. Position 1 represents both wire and terminal before wrapping. Position 2 represents the wire wrapped on the terminal. Position 3 is the same as Position 2 except that the wrapped terminal has been exposed at room temperature (20°C) for eight days. This causes the terminal twist to relax from 46° to 39°. Positions 2 and 3 are analogous to the wire under tension and the terminal under tor-

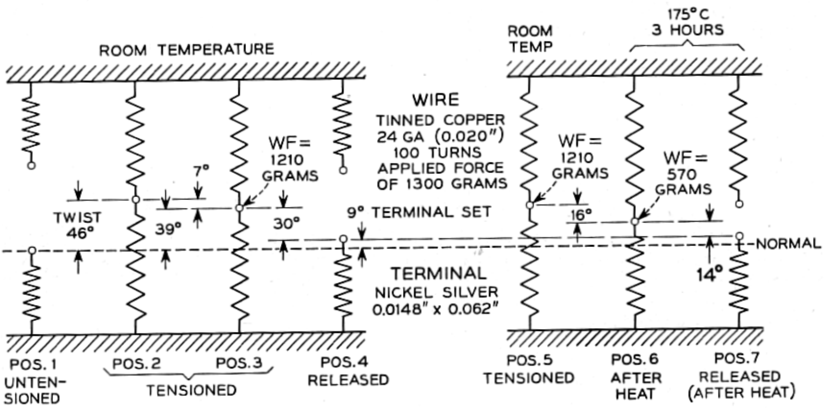


Fig. 12 — Energy in unheated connection proportional to 30°. Energy in heated connection proportional to 14°.

sion. The force WF is the tension in the wrapped wire. This force can be determined by dividing the torque necessary to twist the terminal by the effective moment arm. Since the elongation of the wire cannot readily be measured, the terminal twist was chosen to determine the force exerted at the terminal edge. The 39° terminal twist shown in Posi-

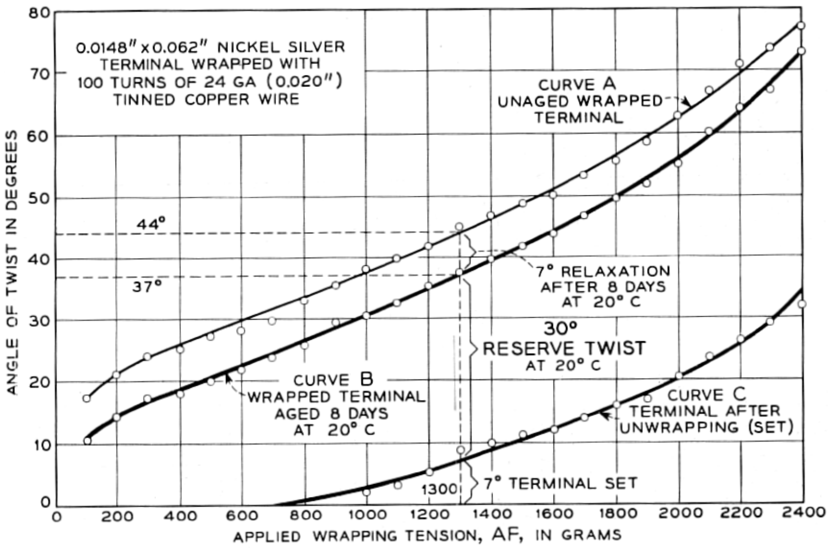


Fig. 13 — Angle of twist in terms of applied wrapping tension.

tion 3, however, cannot be used for determining the force since the terminal may be overstressed as is shown in Position 4. Instead of returning 39° the unwrapped terminal returned only 30°. In other words the terminal has taken a set of 9°. Fig. 12 illustrates the deformation of wire and terminal only for one value of applied tension, namely 1300 grams. If the angle of twist is measured for applied tension ranging from 100 to 2400 grams, a set of curves is obtained as shown in Fig. 13. Curve A shows the angle of twist immediately after the terminal is wrapped. Curve B shows the relaxation after eight days aging at room temperature. Curve C represents the terminal set. The value between Curves B and C is the elastic reserve. For 1300 grams applied tension the elastic reserve is expressed as 30° reserve twist.

Using the before mentioned ratio of torque and moment arm, the force WF can now be determined. The torque required to twist the terminal 30° is 37.2 inch grams. (See Fig. 14.) The effective moment

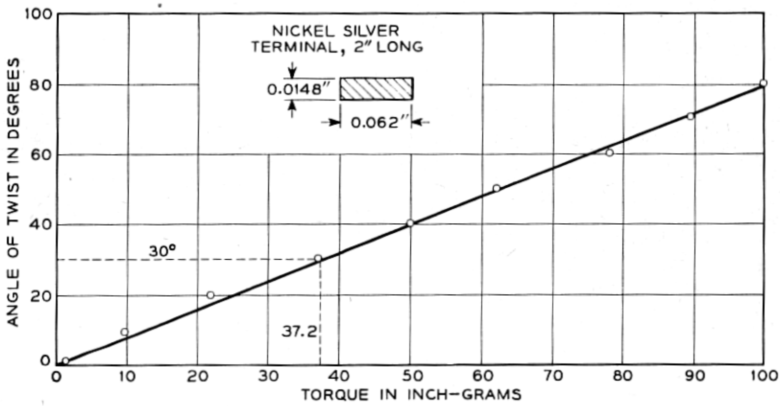


Fig. 14 — Torque required to twist the unwrapped terminal.

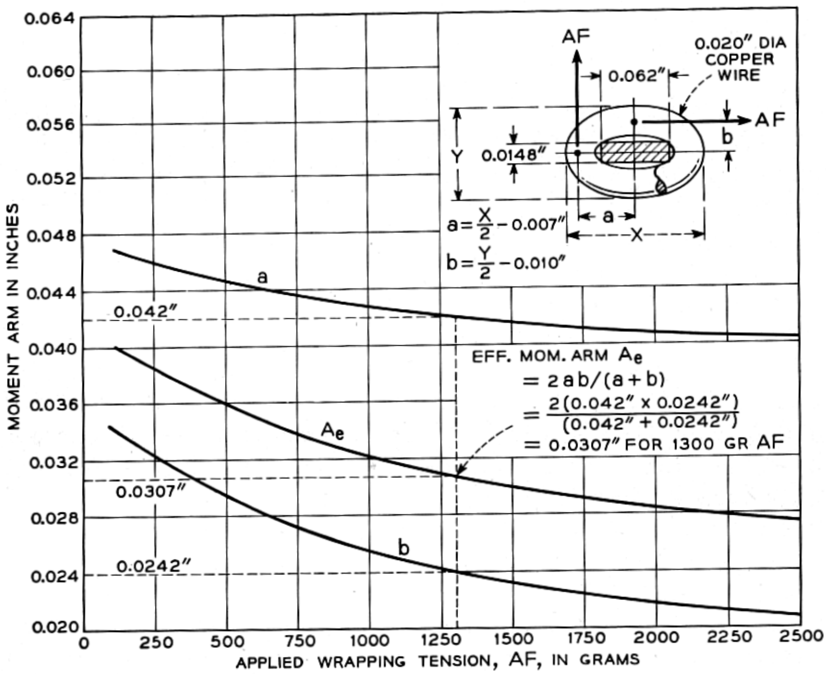


Fig. 15 — Moment arm in terms of tension.

arm A_e, which decreases a slight amount as the wrapping tension AF increases (see Fig. 15), is equal to $2ab/(a + b)$*. Therefore, $A_e = 2 (0.042'' \times 0.0242'')/(0.042'' + 0.0242'') = 0.0307$ in. Thus the tension in the wire WF $= T/A_e = 37.2/0.0307 = 1210$ grams. Using the recovery angle of the terminal as a measure of force, the tension in the wire can now be plotted in terms of angular twist. This is shown in Fig. 16. It should be noted that the tension in the wire WF (wrapped

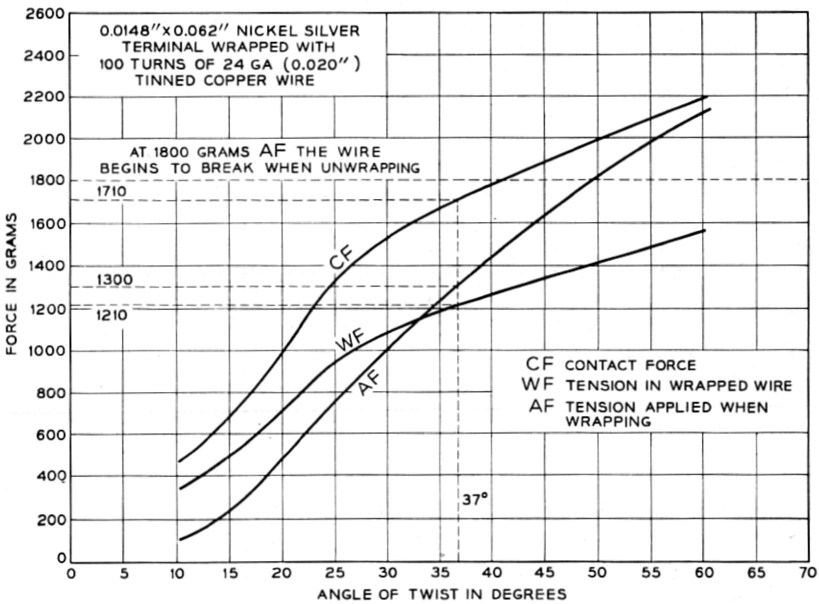


Fig. 16 — Forces in terms of angular twist.

force) is not directly proportional to the wrapping tension AF (applied force). The reason for this is that at low applied wrapping tension the bending of the wire around the corner of the terminal produces an additional increment of tension. For example at an angle of 15° the wrapped tension WF is nearly twice as high as the applied tension AF. The wrapped tension WF and the applied tension AF are about equal when the angle of twist is 33°. At higher values of applied tension, the wrapped tension increases at a much lower rate. This is caused by the terminal taking a set. (See Fig. 13.) At 1300 grams of applied tension, which is the recommended wrapping tension for No. 24 copper wire, the wrapped tension is 1210 grams.

* See Appendix I.

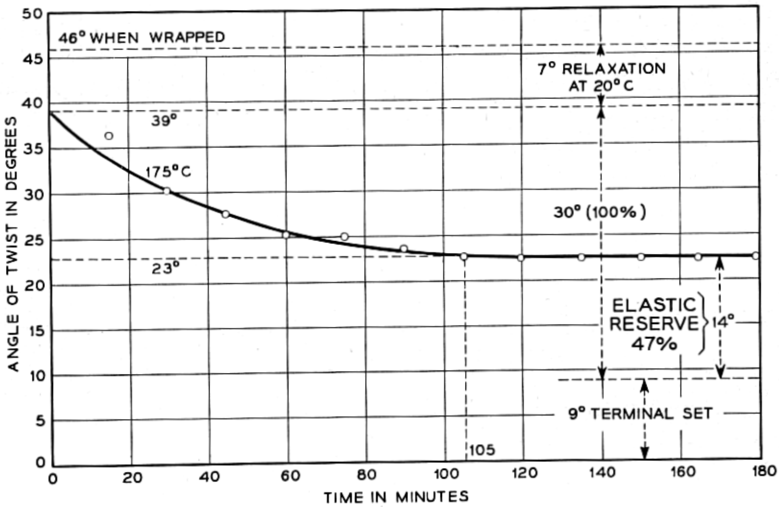


Fig. 17 — Relaxation of wrapped wire after heating for three hours at 175°C. The reserve twist of 14° is an indication of the tension left in the wire which amounts to 47 per cent of the original wrapped tension.

A severe test for a wrapped connection is heating to 175°C for three hours. This relaxes, about half the stress and is considered the equivalent of a 40-year life at 135°F. Position 5 in Fig. 12 is the same as Position 3, that is, the wire has just been wrapped onto the terminal and its tension is 1210 grams. If this connection is now heated to 175°C and the angle of twist noted every fifteen minutes, a curve is obtained as shown in Fig. 17. It should be noted that at 105 minutes the curve is for all practical purposes asymptotic at an angle of 23°. If the heated connection is cooled and unwrapped and the set in the terminal measured, it is found to be 9°. The 14° difference is a measure of the elastic reserve. This is 47 per cent of the wire tension before heating. The corresponding tension WF is then 570 grams. This process is illustrated in positions 6 and 7 of Fig. 12. Position 7 shows that the terminal set of 9° was the same as before heating.

A similar experiment was made with formex insulated wire wrapped on a nickel silver terminal. Instead of subjecting the connection to the heat of an oven, a high current was passed through the wire. Essentially the same curve as shown in Fig. 17 was obtained.

To further check the behavior of springs with complex elastic deformation such as in a wrapped connection on a terminal having edges, measurements were also made with simple helical springs tensioned within the yield point. Two springs, one of nickel silver wire and the other of copper wire having a stiffness ratio of 5 to 6, were coupled in series (Fig. 18), tensioned to 30 grams and then heated to 173°C for two hours. The tension left after heating was 13 grams or 43 per cent of the original tension. The tension decay curve was similar to that shown for the wrapped connection. (See Fig. 17.) This test shows that in spite of the complex deformation of the wire at the corners of the terminal there is substantial agreement in results of the measurements obtained — namely 43 per cent remaining stress in the case of the helical spring and 47 per cent for the wrapped connection.

STRESSES IN THE FINISHED CONNECTION

Having determined the interacting forces in the solderless wrapped connection, the next questions of primary interest are — what are the stresses in various parts of the connection and what will happen to these stresses in forty years?

Most of the elastic energy stored in the wire is in the portion marked "Medium Tension" (Fig. 4). Here the stress is about 8,500 P.S.I. This assumes that a 20-mil wire is wrapped with 1300 grams applied force. The wrapped force or the useful force obtained from the elastic reserve is then 1210 grams.

The stresses at the corners are not easily determined because they are not uniform. This is shown in Fig. 5. As can be seen, the point of highest

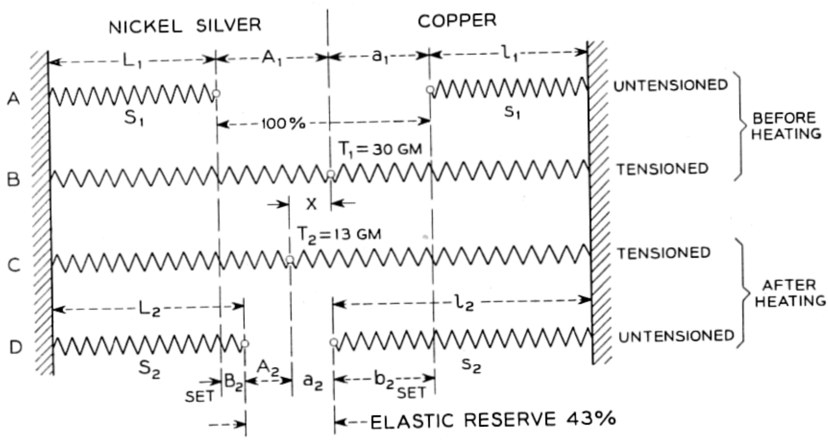


Fig. 18 — Tension T_2 in coupled springs after heating for two hours at 173°C is about 43 per cent of the original tension T_1. (Tension T_1 approximately 10 per cent below the yield point).

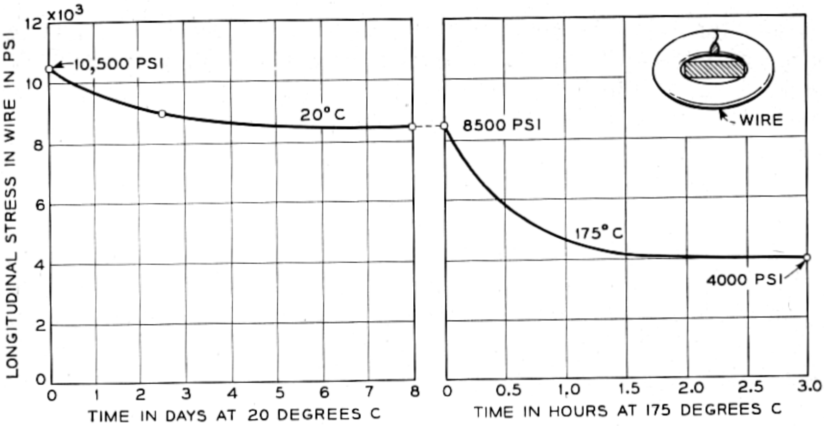


FIG. 19 — Stress relaxation in wire.

concentration is in the center of the contacting area. From this point to the periphery there is a pressure gradient which is similar to that of a circular compressed thin film of viscous material. At the boundary line the pressure is zero. The average pressure within the contact area is about 29,000 P.S.I. but the maximum stress in the center of the contact area may be as high as 100,000 P.S.I. The relaxation, that takes place in eight days at room temperature (Fig. 13), is assumed to be due to the very high initial stress in the center of the contact area which seeks equalization.

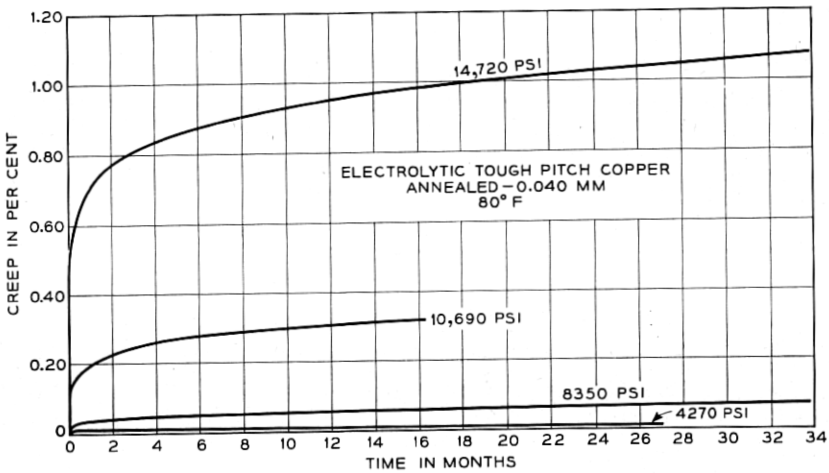


Fig. 20 — Creep curves of annealed copper for various stresses. (Courtesy of Chase Brass and Copper Co., Waterbury, Conn.).

Summarizing the stresses in the connection, one may therefore say that in the portion of the wire where most of the elastic energy resides, the stress after eight days is about 8,500 P.S.I. and at the points of contact 29,000 P.S.I. After forty years these stresses will be approximately 4,000 and 13,500 P.S.I., respectively or 47 per cent of the original stress. (See Fig. 19). As may be seen in the creep curves shown in Fig. 20, a stress of 8350 P.S.I. reaches a creep value of about 0.07 per cent in three years and from then on for all practical purposes ceases to creep.

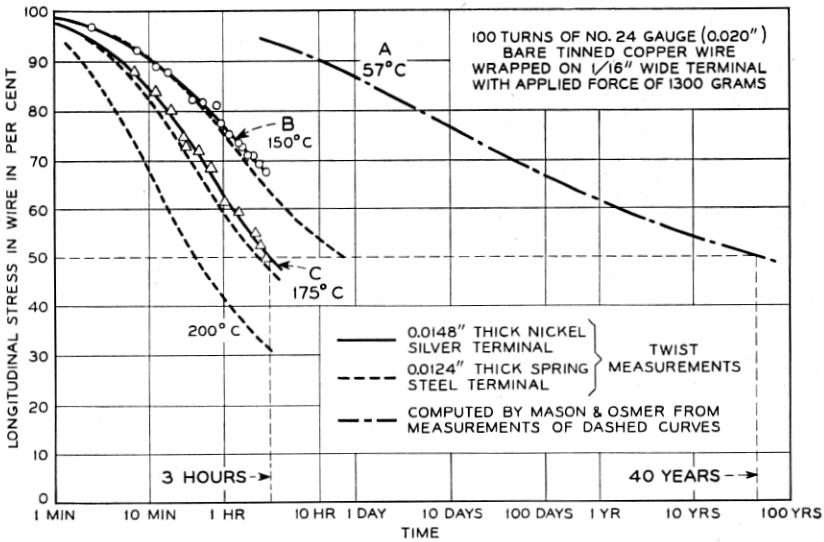


FIG. 21 — Stress relaxation in wire plotted on a logarithmic time scale.

The effect of time and temperature on the longitudinal stress in the wire can better be seen by curves plotted on a logarithmic time scale (Fig. 21). The initial stress after transient relief of three days is considered as 100 per cent. Curve A shows that at a temperature of 57°C (135°F) — which is the maximum temperature that solderless wrapped connections will be subjected to — the longitudinal stress relaxes approximately 50 per cent in 40 years. To reach the 50 per cent value at a temperature of 175°C takes approximately three hours (Curve C). Curves B and C show that the relaxation in the wire is essentially the same for either nickel silver or spring steel terminals.

METHOD OF WRAPPING

In nearly all soldered connections where a wire is to be joined to a terminal the procedure is as follows: The operator takes the skinned

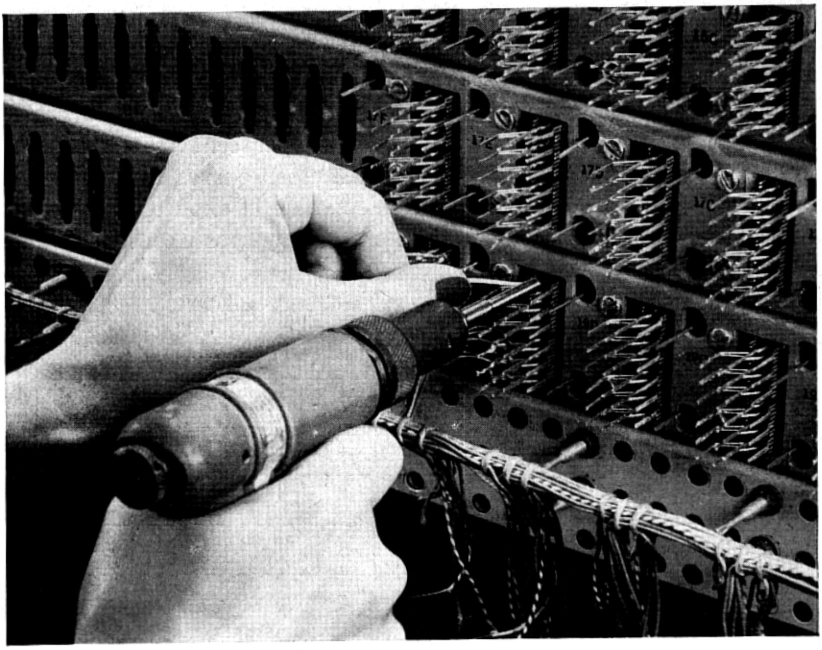


Fig. 22 — Air-driven wiring tool.

end of an insulated wire, hooks or threads it onto the terminal and applies solder. The hooking or threading is important because it is customary in production to attach several wires at first and then solder. The question now is: If a similar procedure is to be followed with a wrapped connection where the wire must surround the terminal with a high pressure, how do we produce that pressure?

In a screw connection a force is obtained by a high lever ratio. In a crimped connection the force is applied by heavy and powerful compression tools. These tools are not suitable for connecting wires to closely spaced terminals such as shown in Fig. 22. To produce high tension in the wire while it is being wrapped onto the terminal, a new method of tensioning had to be devised.

In the manufacture of helical springs it is customary to anchor the end of the wire in a hole in the arbor and tension the wire with a friction pad. By rotating the arbor a helical spring is produced. For closely spaced terminals this method is not practical as the wire cannot be fed tangentially to the terminal and the terminal cannot be rotated. A new wire connecting concept was proposed whereby a rotating spindle housed a stationary terminal in an axial opening in the spindle and was provided with a second opening radially separated from the axial opening and arranged to accommodate a wire. When the spindle was rotated the wire was caused to form a spiral about the stationary terminal. One method involved anchoring the wire in the second opening and feeding the wire tangentially to the terminal as the spindle was rotated. Due to certain limitations inherent in tangential feed onto a stationary terminal an improved method was finally chosen. This is the axial feed method which is particularly adapted to wrapping closely spaced terminals of all cross sections. The operation of loading the wire and wrapping the connection is shown in Fig. 23. Position A shows the tool tip, Position B the bare wire 2 inserted into the feed slot 4, Position C the anchoring of the wire by bending it into the notch 5, Position D the terminal insertion and Position E the wrapping of the wire 2 by rotating the spindle 1 around the terminal 3. Position F is the finished connection. A more detailed drawing of the tool tip is shown in Fig. 24.

WRAPPING TENSION

The tension in the wire is produced by rotating the spindle 1 around the terminal 3 (Fig. 24) thus pulling the short skinner wire 2 out of the feed slot 4. In the process of pulling the wire out of the slot and wrapping it around the terminal each increment of the skinner wire length undergoes several bending operations. The first bending occurs at the edge *R* of feed slot 4 where the wire is bent through an angle of less than 90°. The second bending is the straightening out operation of the bent wire. The third bending takes place as the wire is wrapped around the terminal. All three bending processes contribute to the tension with which the wire is wrapped. The dimensions which control the tension and are therefore of engineering importance are the radius *R* at the tool tip (See Figs. 25 and 25(a)) and the wall thickness *W* (Fig. 24). The bending forces are inversely proportional to the respective bending curvatures and the frictional forces in turn are proportional to the bending forces. The tension imparted into the wire as it is wrapped around the terminal, however, is not only due to the friction alone but to the combined effect of friction and bending effort. If the wire were completely elastic and the friction zero, no tension could be produced. But there would be tension in the wire if the friction were zero and the wire only partly elastic such as copper wire. There also would be tension if a completely elastic wire would be pulled around an edge having friction.

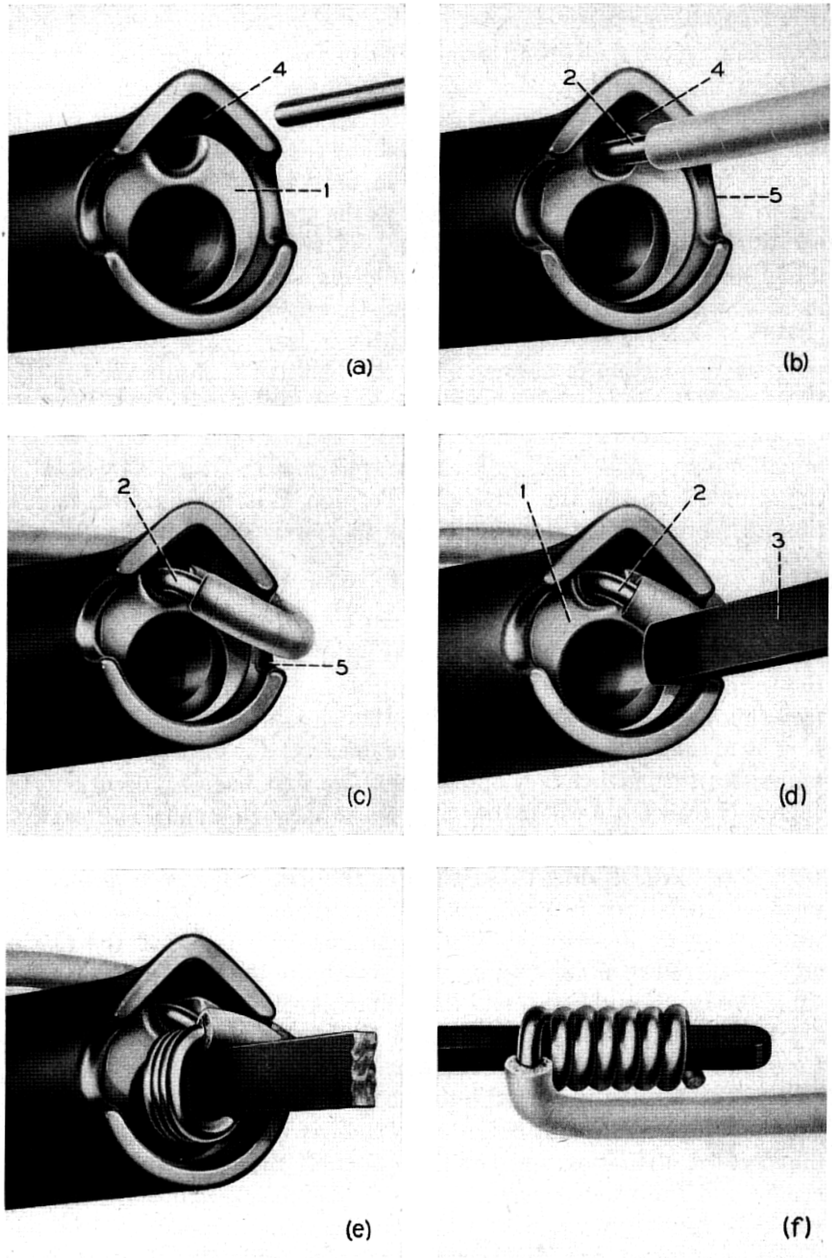


Fig. 23 — The wrapping process. A — Tool Tip. B — Wire Inserted. C — Wire Anchored. D — Terminal Insertion. E — Wire Wrapped. F — Finished Connection.

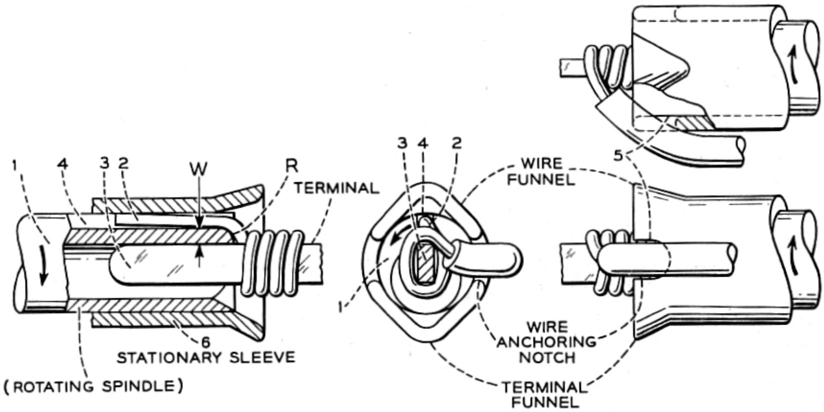


Fig. 24 — Method of wrapping the skinner wire on a rectangular terminal.

CLOSELY SPACED TERMINALS

When the terminals are closely spaced the stationary sleeve 6 and the anchoring notch 5 are used in order to anchor the first turn of wire to the terminal. (See Fig. 26.) However, when the terminals are not closely spaced the sleeve and notch are desirable but are not necessary since the insulated portion of the wire can be held by some means external of the tool at an angle of approximately 90° with respect to the tool spindle. The high acceleration of the wrapping motor produces a mass reaction of the wire leading up to the terminal. This counterforce coupled with a slight tension of the supply wire applied by the external

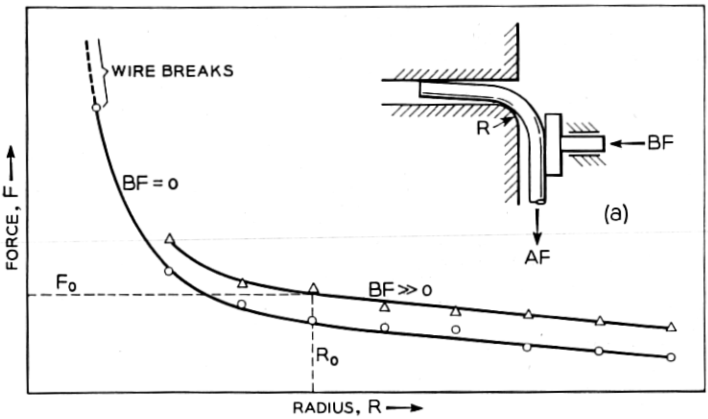


Fig. 25 — Wrapping tension is controlled by edge radius.

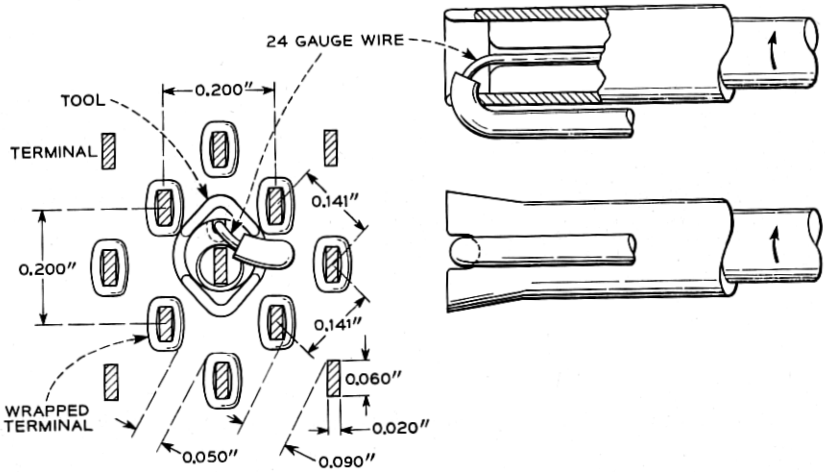


Fig. 26 — Space occupied by wrapping tool between closely-spaced terminals.

wire guiding means is sufficient to insure wrapping of the first turn. The following turns need no further anchor as the first turn locks the wire to the terminal.

The trend toward making circuit components smaller is now marked in all branches of communication engineering. With a tool tip such as

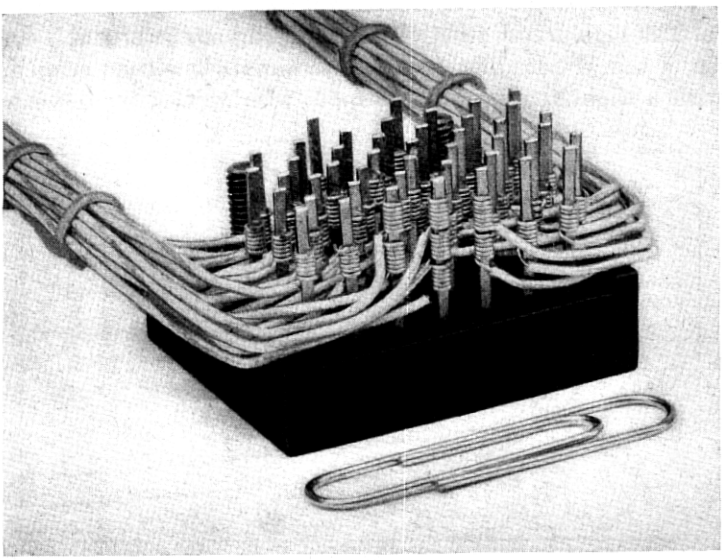


Fig. 27 — Forty-four point terminal block, 132 connection capacity, only 48 connections of 26 gauge (0.0159″) wire shown. Occupies 1⅛″ x ¾″ x 9/16″ or ½ cu in of space.

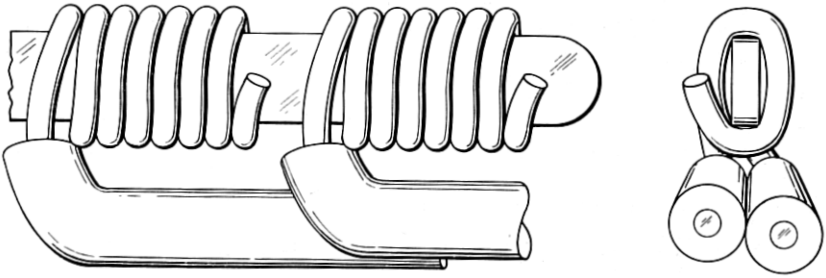


Fig. 28 — Double connection.

shown in Fig. 24, it is possible to wire apparatus having a terminal spacing as close as 2½ times the terminal width. (See Fig. 26.) A terminal block 1⅛″ by ¾″ by 9/16″ having 44 terminals is shown in Fig. 27. The cables shown contain forty-eight No. 26 (0.0159″ dia.) wires all wrapped on the terminals. Each terminal is capable of accommodating three wires or a total of 132 connections may be made in an area of less than one square inch. An enlarged view of a double connection is shown in Fig. 28.

REMOVAL OF CONNECTION

The solderless wrapped connection may be removed from its terminal by two methods. The most convenient method is by stripping. Two types of tools may be used for this purpose. The specially formed jaws of a pair of pliers are hooked in the back of the connection as shown in Fig. 29. By applying a force the connection may be stripped off. The other tool for stripping is shown in Fig. 30. The stripping force varies with the tightness of the wrapping and is plotted in terms of applied

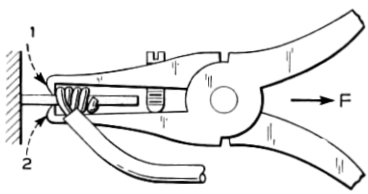


Fig. 29 — Stripping of solderless wrapped connection.

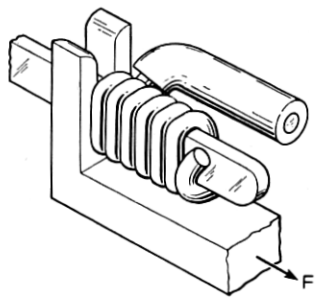


Fig. 30 — Stripping a solderless wrapped connection from a terminal.

wrapping tension in Fig. 31. Another method of removing a connection is by unwinding the helix. This may be done by using a pair of pliers as shown in Fig. 32. Either end of the wire may be used for unwrapping.

A terminal is not seriously damaged by stripping off a wrapped wire, however, the re-use of the stripped off wire is not recommended. A wire may be reconnected by skinning to the proper length and wrapping. When the wire is not sufficiently long to provide the necessary number of turns to insure a good connection, one or two turns may be wrapped and then soldered.

CONNECTION OF LARGE AND SMALL WIRES

There is no upper limit to the size of wire wrapped on adequately proportioned terminals. Connections have been made with both aluminum and copper wire over 200 mils in diameter with satisfactory results. The torque necessary to wrap large wire is considerable, since it increases with the third power of the diameter. A 20-mil wire requires a winding torque of 100 inch grams whereas, a 200-mil wire requires 100,000 inch grams (18 foot pounds). Wires as small as No. 39 (0.0035″ dia.) may also be wrapped, however, the design of the wrapping tool must be changed slightly in order to facilitate the loading of the fine wire into the tool.

DIMENSIONAL RELATIONS

The data given in this paper refer only to No. 24 copper wire 20 mils in diameter. The terminal width most frequently used in conjunction with this size wire is about one-sixteenth inch or three times the wire diameter. The terminal width may also be twice the wire diameter or slightly less, however, the one-sixteenth inch size has been chosen for

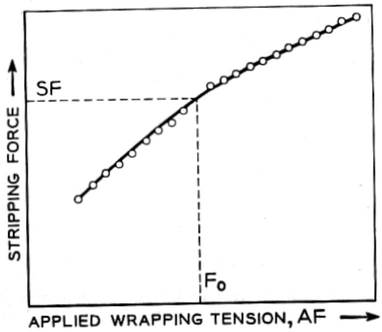


Fig. 31 — Stripping force in terms of applied wrapping tension.

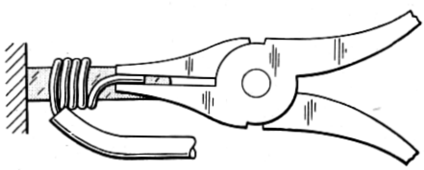


Fig. 32 — Unwinding wrapped connection with pliers.

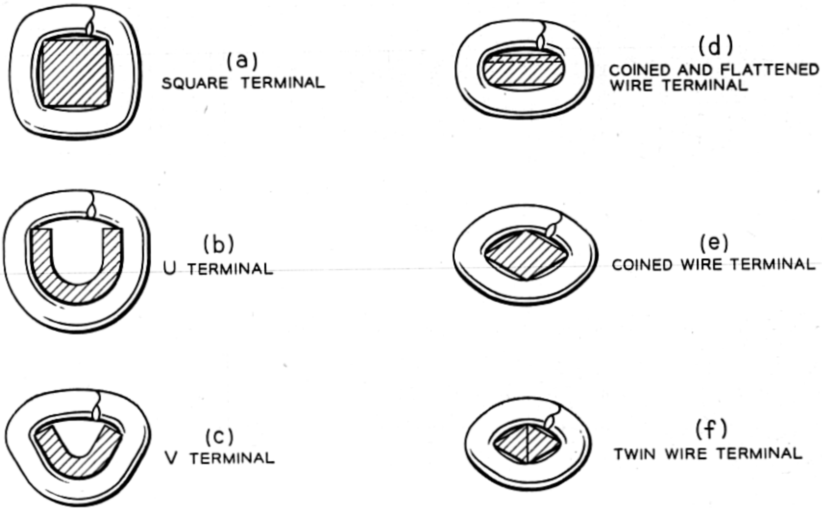


Fig. 33 — Various terminals.

good visibility. When smaller wires are used, the tendency is to make the terminal width greater than three times the wire diameter for better visibility. The terminal thickness depends to a great extent on the shape of the terminal. For a rectangular terminal the thickness may vary from three times to one-half the wire diameter. When the terminal thickness is less than one-half the wire diameter, the terminal may twist too much during the wrapping operation.

TYPES OF WRAPPED CONNECTIONS

The rectangular terminal is not the only terminal which lends itself to a good solderless wrapped connection. Any terminal offering one or more contacting edges substantially crosswise to the axis of the wrapped wire will make a good connection.

Since rectangular terminals of very thin material may twist excessively during the wrapping process the preferred shape is a U or V as shown in Fig. 33. These terminals are capable of storing even more elastic energy than a rectangular terminal of equal cross sectional area. The U and V terminals are particularly suited for vacuum tube sockets and thin relay springs.

Flattened or coined single wires as well as coined twin wires may be used as terminals for solderless wrapped connections. These are shown in Fig. 33.

Stranded wire connections have been made by laying the strands

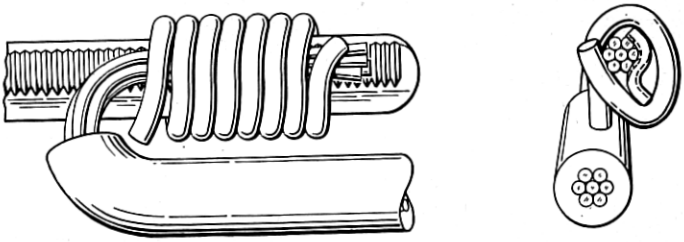


Fig. 34 — Stranded wire connection.

along the serrated edge of the terminal and then wrapping both the terminal and the strands with solid wire. This is shown in Fig. 34. A stranded wire may also be wrapped in the same manner as a solid wire. However, the strands of the wire to be wrapped must be dipped in pure tin in order to bind the strands into the equivalent of a solid wire. A test was made on a No. 24 (0.020″ dia.) wire having seven strands and three twists per inch. The preliminary resistance and aging tests have shown connections of this type to be good.

Enameled wire also has been wrapped. The tool for this purpose has a combination edge at the wrapping tip. Part of the edge has an arc for producing the wrapping tension and the other part has a scraping edge for removing the enamel from the underside of the wire as it is being wrapped onto the terminal.

	1 FAHNESTOCK CLIP NO. 15	2 PLUG 0.040″ DIA. PIN	3 CRIMP 0.120″ DIA. x 0.112″ LG.	4 WIRE NUT 0.350″ DIA. x 0.550″ LG.	5 SCREW NO. 4-40 (0.112″)	6 SOLDERLESS WRAPPED 0.0148″ x 0.062″ TERMINAL
CONTACT FORCE IN POUNDS	1.4	2.2	22	UNKNOWN	135	90
CONTACT AREA IN SQUARE INCHES	0.000079	UNKNOWN	UNKNOWN	UNKNOWN	0.0074	0.0031
CONTACT PRESSURE IN PSI	18,000	UNKNOWN	UNKNOWN	UNKNOWN	18,250	29,000
SPACE 10^6 CUBIC MILS	41	8.78	1.75	52.8	15.6	1.53
ELASTIC ENERGY IN MIL-POUNDS	21	UNKNOWN	UNKNOWN	UNKNOWN	2.77	3.05

Fig. 35 — Comparison of pressure connections for No. 24 (0.020″) wire.

EVALUATION

The solderless wrapped connection has been compared with other pressure connections. (See Fig. 35.) However, when compared with a soldered connection its advantages are as follows:

1. A substantial reduction in wiring defects in manufacture and in service because of:—
   a. Greater uniformity obtained with a calibrated tool.
   b. Less breakage of wires due to handling and vibration.
   c. No solder splashes.
   d. No clippings.
   e. No cold joints.
   f. No rosin joints.
2. Less expensive connection.
3. More compact connection.
4. More clearance between current carrying parts.
5. Easy to disconnect.
6. Saving of tin — a critical material.
7. No contact contamination from soldering fumes.
8. No damage to heat sensitive materials in circuit components.
9. No hazard from hot soldering iron.

SUMMARY

A good pressure connection depends on the amount of elastic energy which can be stored in the mutually stressed members, namely the wire and terminal. If the ratio of elastic energy to the size of the connecting members is favorable, and the contacting areas are sufficiently large, then the connection can be termed good. The solderless wrapped connection when properly proportioned not only meets these requirements, but is uniform in quality and low in cost.

Appendix I

EFFECTIVE MOMENT ARM FOR TORSION OF RECTANGULAR TERMINAL

In this appendix the relationship between the wrapped tension in the wire and the twist of the terminal will be analyzed. The structure of the solderless wrapped connection is equivalent to a terminal having springs attached between its edges as shown in Fig. 36. The springs are arranged in such a way as to form a helix of pitch p. Now let:

S_u = torsional stiffness of a unit length terminal

WF = wrapped tension

$2a$ and $2b$ be the sides of the rectangular cross section of the terminal.

ℓ_1 = lead of wire helix on long side ($2a$).

ℓ_2 = lead of wire helix on short side ($2b$).

N = number of turns of wire

The classical formula for Torsion is

$$\theta = \frac{\text{Torque} \times \text{Length}}{S_u} \tag{1}$$

For an equivalent "spring" attached to the long side the axial length of the terminal is ℓ_1, the torque is WFb* and hence the deflection $WFb\ell_1/S_u$; for the short side the length is ℓ_2, the torque is WFa* and the deflection $WFa\ell_2/S_u$. For a complete turn of the helix the length of the terminal is therefore, $2(\ell_1 + \ell_2) = p$, and the torsional deflection is

$$\delta = \frac{2WF}{S_u}(b\ell_1 + a\ell_2) \tag{2}$$

It is logical to assume that

$$\frac{\ell_1}{\ell_2} = \frac{a}{b} \tag{3}$$

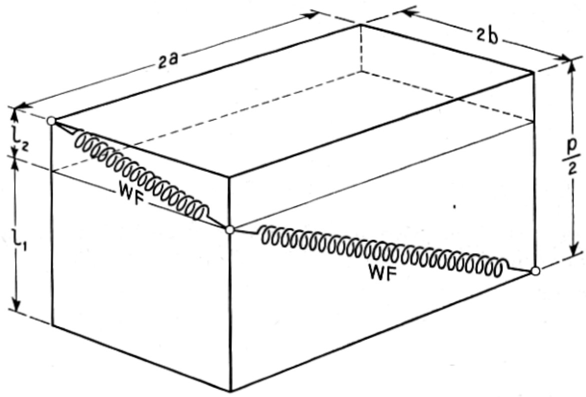


Fig. 36 — Equivalent structure of wrapped connection (only half turn shown).

* This is approximate and holds closely for $\ell_1 \ll 2a$ and $\ell_2 \ll 2b$

Substituting (3) into (2), the deflection per turn becomes

$$\delta = \frac{2ab}{a + b} p \frac{WF}{S_u} \tag{4}$$

Since all effective turns are similar the total deflection Δ for N turns is

$$\Delta = WF \left[\frac{2ab}{a + b} \right] \frac{(pN)}{S_u} \tag{5}$$

pN is the total length of the terminal. By equation (1) the effective torque must then be

$$\text{Torque} = WF \left[\frac{2ab}{a + b} \right] \tag{6}$$

and hence the effective moment arm, A_e

$$A_e = \left[\frac{2ab}{a + b} \right] \tag{7}$$