Evaluation of Solderless Wrapped Connections for Central Office Use

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(Manuscript received September 10, 1958)

In the development of solderless wrapped connections for telephone central office applications, the general reliability objective has been that the connections should remain mechanically secure and electrically stable during manufacture, shipment and installation and for 40 years thereafter in actual service. Destructive mechanical tests have been used to evaluate the mechanical properties of the connections. Combinations of elevated temperatures and mechanical disturbances have been used to accelerate the aging processes that tend to cause electrical instability. The results of such tests have provided considerable assurance that properly designed and properly made solderless wrapped connections will perform satisfactorily for 40 years in central office service.

I. INTRODUCTION

Since 1952, when the solderless wrapped connection first was described publicly,[1] its use in telephone central offices has grown steadily. Several hundred million solderless connections are being wrapped annually in the Bell System today, and the growth is continuing.

The tangible and immediate results of solderless wrapping have been gratifying. For example, the use of solderless wrapping has reduced manufacturing costs by speeding up many wiring operations and by reducing troubles caused by wire clippings and solder splashes. Furthermore, since solderless wrapping avoids the risk of damaging heat-sensitive insulation by soldering operations, it has made widespread use of plastic-insulated wire practicable, and this is leading to substantial additional savings.

In the end, however, these savings could be illusory if the use of solderless wrapped connections degraded telephone service or increased the maintenance effort required in the telephone plant. The laboratory evaluation of solderless wrapped connections has been continued, therefore, in order to assess the risk of deterioration in service and to provide guidance for the design of connections that are most likely to be reliable. This work has revealed certain limitations of solderless wrapped connections, but, at the same time, it has provided considerable assurance that properly designed and properly made connections will be reliable in central office service.

Many persons have inquired about the methods used for evaluating the capabilities of solderless wrapped connections and about the results that have been obtained since publication of earlier articles.[2,3] Since the inquiries continue undiminished year after year, it appears that there is sufficient interest in solderless wrapping to warrant another paper on the subject. An attempt is made here, therefore, to bring the story on evaluation up to date.

1.1 *Description of Solderless Wrapped Connection*

A solderless wrapped connection is made by wrapping a wire tightly around a terminal, and the connection is held together thereafter by the elastic stresses left in the two members. A typical solderless wrapped connection is shown in Fig. 1.

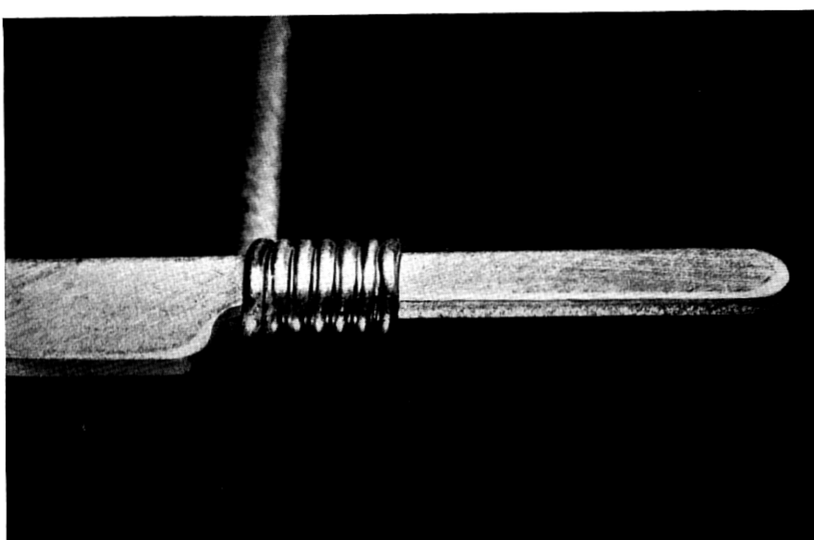


Fig. 1 — Typical solderless wrapped connection.

For Bell System applications, a minimum of five turns of wire is specified when No. 22 gauge wire is used, and a minimum of six turns is specified when No. 24 gauge wire is used. The wire should be closely wound on the terminal, but turns of wire should not overlap.

Only solid copper wire has been approved for solderless wrapping. The use of stranded wire presents a number of difficulties and has not been investigated in detail.

1.2 *Reliability Objectives*

The general reliability objective in the development of solderless wrapped connections has been that the connections should remain mechanically secure and electrically stable during manufacture, shipment and installation and for 40 years thereafter in telephone central office service.

The mechanical security objective cannot be defined in absolute terms, for too little is known about the magnitudes and distributions of the disturbances to which wires are subjected in service. As a comparative objective, however, solderless wrapping should not increase the occurrence of broken wires and loose connections beyond the levels that now prevail with soldered connections.

The electrical stability objective can be stated more specifically. Not more than one connection in 10,000 should exhibit resistance fluctuations greater than 0.1 ohm in service. The electrical noise produced by resistance fluctuations of this magnitude is considered to be at the threshold of transmission impairment in the most critical transmission circuits now in service.

II. ELECTRICAL MEASUREMENTS

The method used for checking the electrical stability of solderless wrapped connections has been described fully by Van Horn.[2] In essence, it consists of a resistance measurement made by the familiar voltmeter-ammeter method. The voltage drop across the connection is measured with a moving coil millivoltmeter while a direct current of 0.1 ampere flows through the connection.

The measurement of interest is the *variation* of resistance when the connection is disturbed mechanically. The disturbance is created by plucking the terminal — that is, by slowly deflecting the free end of the terminal a predetermined distance and then releasing it abruptly, allowing terminal and connection to vibrate freely. The resistance variation

(ΔR) is the difference between the maximum and minimum resistance values observed during the disturbance.

Although the moving-coil millivoltmeter is too sluggish to follow rapid fluctuations of resistance, the measurement is surprisingly sensitive. In a series of measurements made by an appropriate electrical noise meter while connections were subjected to vibration of the sort encountered in service, the measured noise levels consistently were lower than the levels calculated from the results of the simple ΔR measurements. It was concluded that the simple ΔR measurement would be adequate for routine development tests and, since it could be made far more rapidly than any of the more refined measurements that had been explored, it was adopted.

2.1 *Analysis of ΔR Measurements*

Before reviewing the accelerated aging tests that have been employed in the evaluation of solderless wrapped connections, it is necessary to describe the method that will be used to summarize the results. This method, a product of hindsight rather than foresight, has been used for only a short time in development of the solderless wrapped connection.

A major problem in the evaluation, of course, has been to demonstrate by means of comparatively small samples that the probability of ΔR exceeding 0.1 ohm is no more than one in 10,000. The expense of testing large enough samples to determine the frequency distribution of ΔR in every case would have been prohibitive. Over a period of years, however, a moderately large number of tests were made on a few particular types of connections. The cumulative sample sizes in those cases, although still small compared with 10,000, were large enough to warrant attempts at curve fitting.

As measured by the chi-square test, the expression that seems to fit the observed distributions best is obtained by first grouping the ΔR data in cells as follows:

Cell Number, x	ΔR (Ohms)	Number of Connections in Cell
0	$0 \leqq \Delta R \leqq 0.001$	n_0
1	$0.001 < \Delta R \leqq 0.01$	n_1
2	$0.01 < \Delta R \leqq 0.1$	n_2
3	$0.1 < \Delta R \leqq 1.0$	n_3
···	···	···
etc.	etc.	etc.

The arithmetic mean of the grouped distribution then is calculated as follows:

$$m = \frac{0n_0 + 1n_1 + 2n_2 + 3n_3 + \cdots}{n_0 + n_1 + n_2 + n_3 + \cdots} = \frac{n_1 + 2n_2 + 3n_3 + \cdots}{N}, \tag{1}$$

where N is the total number of connections in the sample.

Once the mean, m, has been calculated, the probability of finding a connection in cell x can be expressed as

$$P_x = \frac{m^x e^{-m}}{x!}. \tag{2}$$

Bearing in mind that $0! = 1$, the probabilities associated with the first few cells become

$$\begin{aligned} P_0 &= e^{-m}, \\ P_1 &= mP_0, \\ P_2 &= \frac{mP_1}{2}, \\ P_3 &= \frac{mP_2}{3}. \end{aligned} \tag{3}$$

The reader may recognize that (2), the general expression for P_x, is the same as the expression for the Poisson distribution. The physical interpretation, however, is different. In the Poisson distribution, P_x is the probability that x defectives will occur in a random sample of size N if m is the expected average number of defectives in a sample of that size. As a description of the ΔR distribution, however, P_x is the probability that ΔR, for a single connection chosen at random, will fall between the limits defined by the cell number x. For a random sample of N connections, then, the number of connections expected to fall in cell number x will be NP_x.

In general, the agreement between (2) and observed ΔR distributions has been best for the more stable types of connections — types in which high values of ΔR rarely occur and for which m is small. These, of course, are the types of connections that are desirable. For less stable types of connections — the types that would be rejected as unreliable — the

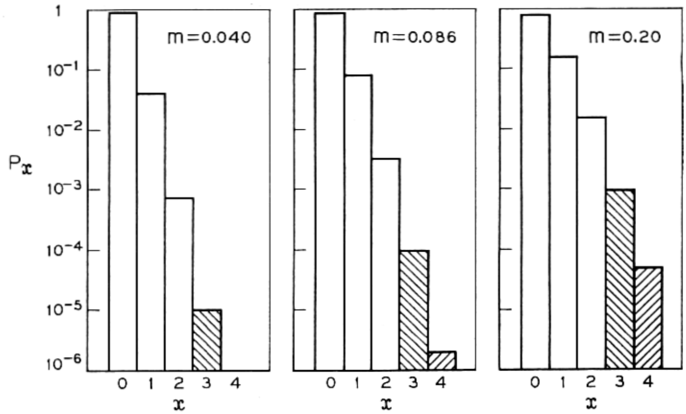


Fig. 2 — Examples of the ΔR distribution defined by (2). Shading indicates cells for which ΔR exceeds 0.1 ohm.

agreement has been poorer. The dividing line between good agreement and poor agreement appears to be somewhere in the vicinity of $m = 0.3$.

The mean, m, is a convenient statistic to use in summarizing the results of a group of ΔR measurements, and it will be used for that purpose in the discussion of accelerated aging tests. Qualitatively, low values of m indicate stable connections and high values indicate unstable connections. Quantitatively, in those cases where m is less than about 0.3, m defines the observed ΔR distribution very effectively.

The distribution corresponding to $m = 0.086$ (shown in Fig. 2) is of particular interest. It represents the case for which there is one chance in 10,000 that ΔR will exceed 0.1 ohm. Consequently, a value of $m = 0.086$ *in service* is the maximum value that will satisfy the stability objective for central office use of solderless wrapped connections in the Bell System.

One more point needs to be made before proceeding to the discussion of accelerated aging tests. The variance of the distribution described by (2) is equal to the mean, m. It follows, then, that the standard deviation is equal to the square root of m. This relationship will be used later in developing criteria for deciding whether or not connections are stable enough to be approved.

III. ACCELERATED AGING TESTS

Fairly early in the development of solderless wrapped connections, it was concluded that electrical instability, if it occurred at all, would result principally from relaxation of stresses in the wire and terminal — the stresses that hold the connection together. Since that time, all aging tests employed in the evaluation of solderless wrapped connections have included elevated temperatures to accelerate the relaxation process.

The work of Mason[2,3] and others indicated that the stress in copper wire (measured with respect to its value one day after a connection was wrapped) would relax about 40 per cent in 40 years at room temperature. To allow for some error in the room temperature prediction, and to allow for the fact that temperatures in enclosed equipments may approach 55°C in some cases, it has been assumed that the stresses in solderless connections wrapped with copper wire may relax as much as 50 per cent under central office conditions. That has been the degree of stress relaxation aimed at in the various accelerated aging tests.

One of the early tests consisted simply of baking the connections for three hours at 175°C. (Mason had shown that the stresses in connections wrapped with copper wire would relax 50 per cent in about $2\frac{1}{2}$ hours at 175°C, and the extra half-hour was needed to bring the specimens from room temperature up to the oven temperature.) At the end of the heat treatment, the connections were cooled to room temperature and then were checked for electrical instability. The general experience was that any solderless wrapped connection which was stable before the heat treatment still would be stable after the heat treatment.

Although such results were encouraging, they were, at the same time, disconcerting. For example, some of the connections that behaved so well in the 175°C test were wrapped on terminals that scarcely could be considered good mechanical structures for supporting stresses over long periods. The twin-wire terminal of the wire-spring relay, in particular, fell in the questionable category. At that time it consisted simply of two parallel nickel silver wires which were bonded together by being dipped in soft solder and then serrated. The parallel wires by themselves did not have sufficient torsional stiffness to support the stresses that are required to hold a solderless wrapped connection together; and soft solder, because of its cold flow properties, is a notoriously poor material for supporting stresses. It was doubtful that the soft solder, at room temperature, could maintain the stresses long enough at levels high enough for solid state diffusion to occur. Since 175°C was not far below the softening temperature of the solder, there was at least a suspicion that something akin to a soldered joint had been produced in the accelerated aging test.

There were questions, also, about the metallurgical behavior of the copper wire at the elevated temperature. It was known, for example, that recrystallization is more likely to occur in copper at 175°C than at lower temperatures.

In short, it was suspected that a temperature as high as 175°C might do more than accelerate the aging process: it might alter the physical nature of the aging process itself. If this were so, then the 175°C test might give a false picture of the aging that would occur in actual service

3.1 *105°C Aging Test*

It was decided, therefore, that some exploratory aging tests should be run at a substantially lower temperature. For several reasons, a temperature of 105°C was chosen. It was well below the softening temperature of tin-lead solders; it was low enough so that there should be little likelihood of recrystallization occurring in the copper wire; yet it was high enough to produce the desired stress relaxation in a few months. Mason's work had indicated that the stresses in the wrapped connections would relax 50 per cent in about 150 days at 105°C, so the test period was set at 150 days, or approximately five months.

As compared with the desired service life of 40 years, the three-hour 175°C test represented a 100,000:1 acceleration of the stress relaxation process. Since a five-month 105°C test would represent an acceleration of only 100:1, it was expected to be a far more realistic aging test.

Five months is a long time, however, to wait for test results. It was decided, therefore, that the test connections should be measured periodically during the aging test, so that any instability would be detected as soon as it occurred. It is important to note that this decision introduced two more changes in the accelerated aging test: (a) it subjected the connections to temperature cycling, for they were removed from the oven and allowed to cool whenever they were measured, and (b) it subjected the connections to mechanical disturbances while they were being aged, for the terminals were plucked whenever resistance variations were measured.

The first connections subjected to the 105°C aging test were wrapped on the solder-dipped twin-wire terminals described earlier. Connections of that type had survived the 175°C test without showing any evidence of instability. In the 105°C test, however, they soon began to exhibit measurable resistance fluctuations, and they grew more and more unstable as the test continued. The history of that first group of connections is plotted in terms of the statistic m in Fig. 3. It was evident that the 105°C aging test with periodic cycling and measurement was more severe than the undisturbed 175°C test.

Subsequently an experiment was performed to compare the relative effects of temperature, temperature cycling and mechanical disturbance. One group of connections was aged at 105°C, cooled to room temperature once each week and measured (plucked) while at room temperature

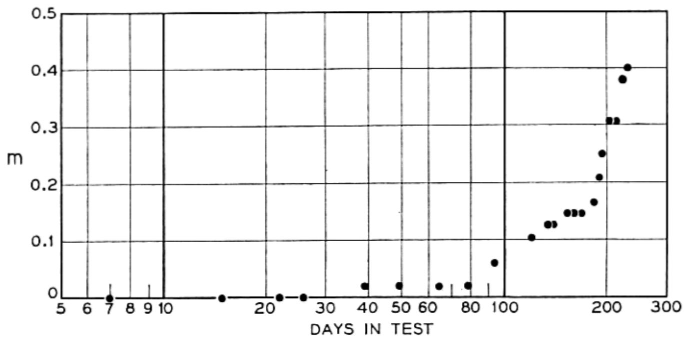


Fig. 3 — Effect of 105°C accelerated aging test on solderless connections wrapped with No. 24 gauge copper wire on solder-dipped twin wire terminals of wire-spring relay. Sample size 48.

on alternate weeks. At the end of 150 days, the value of m for that group was 2.1.

A second group of similar connections was aged at 105°C and cooled to room temperature once each week, but was not disturbed by measurements. After 150 days, m was 0.2.

A third group was aged continuously at 105°C without either temperature cycling or mechanical disturbance. After 150 days, m was 0.04.

A fourth group was maintained continuously at room temperature but measured every two weeks. After 150 days, m was 0.02.

Three important inferences were drawn from the results of this experiment:

i. Although solid state diffusion may occur during undisturbed aging of solderless wrapped connections, thus tending to offset the detrimental effects of stress relaxation, repeated mechanical disturbances during the aging process can impede diffusion and can lead to unstable connections.

ii. Since connections may be disturbed from time to time in service, accelerated aging tests should include periodic mechanical disturbances.

iii. Temperature cycling alone can produce a form of mechanical disturbance if the temperature coefficients of expansion of wire and terminal are not equal.

Another related experiment was performed to study the effects of the frequency with which connections were disturbed during the 105°C aging test. The more frequently the connections were disturbed, the sooner they became unstable. A few of the test results are shown in Fig. 4 to illustrate the pattern.

Long before these two experiments were completed, it had been neces-

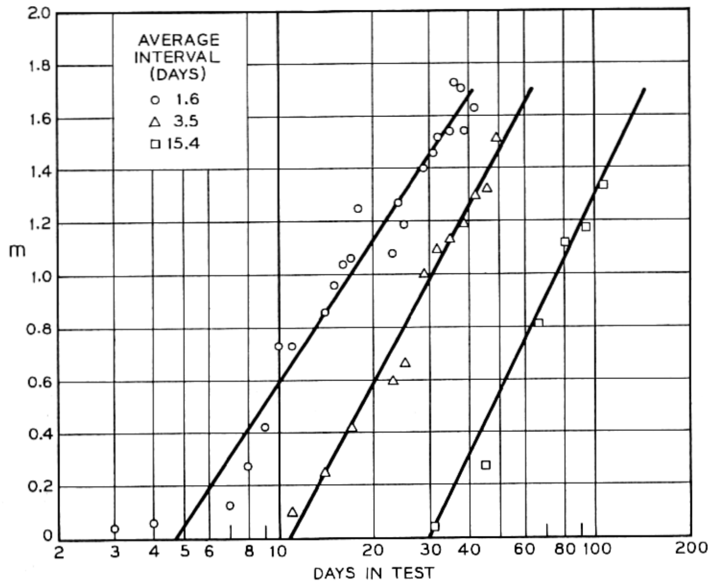


Fig. 4 — Effects of varying the frequency of disturbance in 105°C accelerated aging test. Connections wrapped with No. 24 gauge tinned copper wire on 0.010 × 0.062-inch flat nickel silver terminals. Sample size 48 in each case.

sary to standardize an accelerated aging test so that the development of suitable terminals could proceed without further delay. The 150-day 105°C test was adopted, primarily because it was the only aging test up to that time that had revealed highly significant differences among various types of connections — differences that usually were consistent with qualitative analyses of the various mechanical structures. The connections were cooled to room temperature once each week, and their resistance variations were measured at room temperature every other week. Each connection was plucked two or three times during the ΔR measurement. Eventually, a plucking amplitude of $\frac{1}{32}$ inch was standardized.

A standard procedure for the preparation of test specimens also evolved gradually. It has become the usual practice now, in preparing each group of test connections, to use two wrapping bits (one that wraps more tightly than the average bit, and one that wraps less tightly), two wrapping tools (one power-driven and the other manually operated), two grades of wire (one comparatively hard and the other comparatively soft) and two operators. All 16 combinations of the four parameters now are included at least twice in each test.

3.2 *Results of 105°C Accelerated Aging Test*

Altogether, more than 11,000 solderless wrapped connections have been subjected to the 105°C accelerated aging test. Most of the tests have been aimed at the problem of finding terminal configurations which would yield reliable connections and which, at the same time, could be manufactured economically. The results of a number of those tests are summarized in Table I, along with the results of a screening test that is described in Section 3.4.

Fig. 5 shows the results that were obtained with No. 24 gauge tinned copper wire wrapped on terminals punched from several widely used thicknesses of nickel silver stock. The performance of the thinner terminals was considered to be unsatisfactory. Various types of longitudinal embossing were investigated to find means for improving the thin terminals, and the form shown in Fig. 6 finally was standardized. Although this form is not necessarily optimum, it is a convenient form to manufacture; and it has behaved well in the accelerated aging test, as shown in Table I.

TABLE I — RESULTS OF ACCELERATED AGING TESTS ON SOLDERLESS CONNECTIONS WRAPPED WITH TINNED COPPER WIRE

Type of Terminal	Material	Finish	105°C Aging Test				175°C Screening Test			
			No. 22 Wire		No. 24 Wire		No. 22 Wire		No. 24 Wire	
			N	m	N	m	N	m	N	m
Rectangular										
0.045 × 0.045	Brass	Electrotin	136	0	296	0	168	0	328	0.009
0.0319 × 0.062	Brass	Electrotin	152	0.026	152	0.020	160	0	160	0
0.0319 × 0.062	Nickel Silver	None	152	0	104	0	976	0.15	2050	0.078
0.0253 × 0.062	Nickel Silver	None	—	—	24	0.053	105	0.37	93	0.13
0.0201 × 0.062	Nickel Silver	None	—	—	144	0.084	116	0.88	342	0.16
0.0159 × 0.062	Nickel Silver	None	—	—	24	1.2	—	—	121	0.38
0.0126 × 0.062	Nickel Silver	None	—	—	24	1.8	—	—	203	0.40
0.010 × 0.062	Nickel Silver	None	—	—	96	2.1	—	—	1164	0.42
Embossed										
0.0253 × 0.062	Nickel Silver	None	—	—	—	—	136	0.31	137	0.007
0.0201 × 0.062	Nickel Silver	None	—	—	64	0	—	—	274	0.16
0.0159 × 0.062	Nickel Silver	None	—	—	—	—	—	—	131	0.084
0.0126 × 0.062	Nickel Silver	None	—	—	64	0	—	—	131	0.015
0.010 × 0.062	Nickel Silver	None	—	—	64	0	—	—	180	0.11
Wire-Spring Relay										
Single Wire	Nickel Silver	None	144	0.12	288	0	—	—	144	0.010
Twin Wire	Nickel Silver	None	144	0.021	513	0.006	—	—	749	0.064

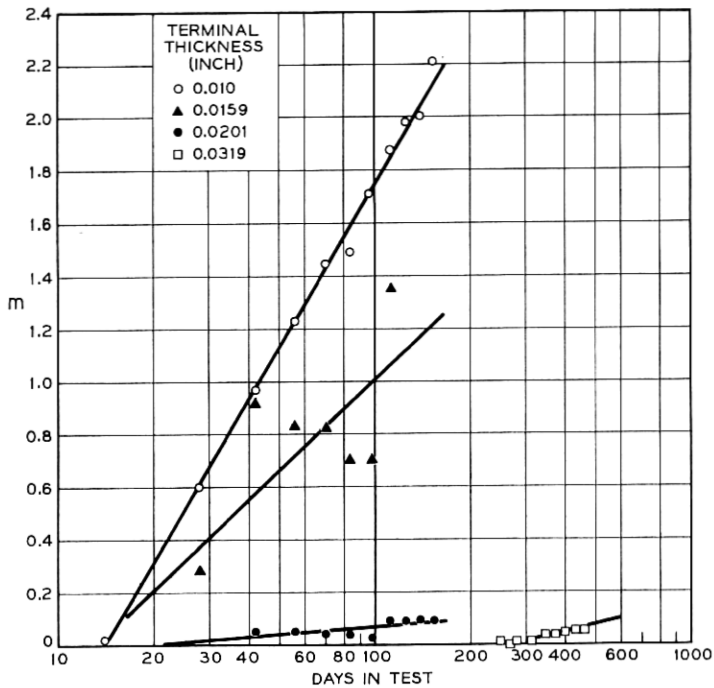
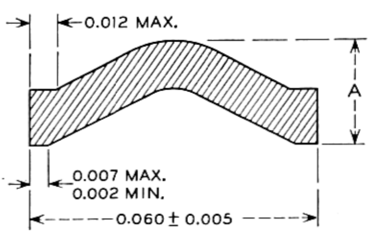


Fig. 5 — Results of 105°C accelerated aging tests. All terminals flat nickel silver, 0.062 inch wide. Connections wrapped with No. 24 gauge tinned copper wire.

The early single-wire terminal of the wire-spring relay was formed from a round wire by flattening, serrating on one side and solder-dipping. Its performance was unsatisfactory, but it was improved simply by omitting the solder. Its present form is shown in Fig. 7.

The twin-wire terminal of the wire-spring relay was more of a problem. Many designs were conceived and investigated, but most of the



NOMINAL THICKNESS OF STOCK (INCH)	DIMENSION A (INCH)
0.010	0.021 ± 0.002
0.013	0.023 ± 0.002
0.016	0.025 ± 0.002
0.020	0.026 ± 0.002

Fig. 6 — Embossing approved for Bell System terminals.

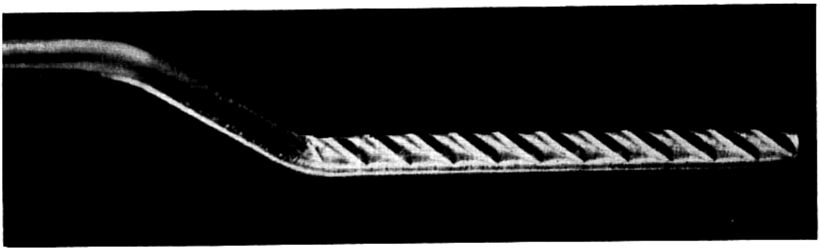


Fig. 7 — Single-wire terminal of wire-spring relay.

designs that showed promise from the solderless wrapping standpoint were objectionable from the manufacturing standpoint. In the end, a compromise design was adopted. The twin wires are twisted tightly together, then they are coined in a closed die which has a trapezoidal cross section. The resulting terminal is shown in Fig. 8.

Although most of the 105°C tests have been made with No. 24 gauge wire, a number of tests have been made also with No. 22 gauge wire. As shown in Table I, the results indicate that No. 22 gauge connections on the heavier terminals are as stable as No. 24 gauge connections, but that No. 22 gauge connections on the lighter terminals are inferior.

The aging tests of No. 26 gauge connections are not completed yet. The preliminary results indicate, however, that No. 26 gauge connections, even when wrapped with as many as nine turns of wire, are less stable than six-turn No. 24 gauge connections on the same types of terminals.

For certain types of wiring in the Bell System, it has been standard practice to use untinned copper wire. Solderless connections wrapped with untinned wire, however, tend to deteriorate sooner than connections wrapped with tinned wire. Fig. 9 illustrates results obtained with untinned wire.

The data that have been presented so far should be sufficient to provide a bird's-eye view of the results that have been obtained in the

Fig. 8 — Twin-wire terminal of wire-spring relay.

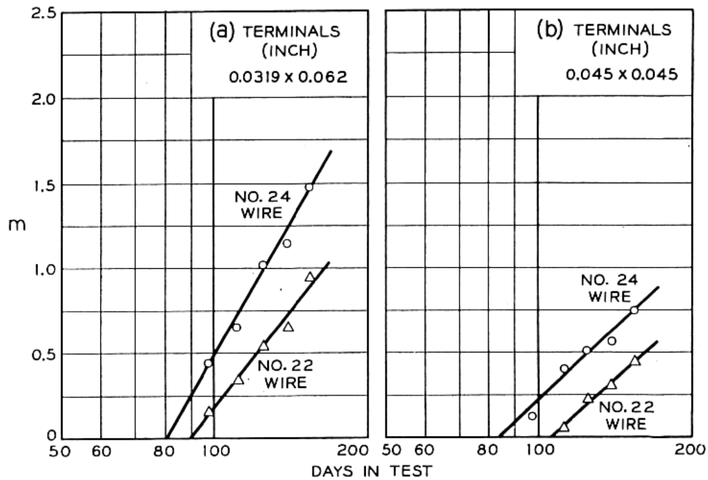


Fig. 9 — Effect of 105°C accelerated aging test on connections wrapped with untinned copper wire on electrotinned brass terminals. Sample size 32 in each case.

105°C aging test. Other alleys and byways have been explored, but the picture would not be sharpened perceptibly by presenting more details. It is more pertinent at this point to consider what use can be made of the test results.

3.3 *Criterion for Acceptance (105°C Aging Test)*

The purpose of the accelerated aging test, of course, is to distinguish between those types of solderless wrapped connections which are likely to satisfy the 40-year stability objective in service and those types which are not likely to satisfy the objective. The test results supply a reasonably clear picture of the relative instability of the several types of connections, but this by itself is not enough. Somewhere on the instability scale the development engineer eventually must draw a line and say, at least to himself, "I will approve the use of types of connections that fall below this line; I will not approve types that fall above it." In other words, he must establish a criterion for acceptance.

The criterion for acceptance has not remained static as the development of solderless wrapped connections progressed. Instead, it has been revised several times as the aging test evolved and as the information obtained from aging tests expanded. Its present form has considerably more meaning and is more convenient to use than some of the earlier forms.

The criterion for acceptance is based upon two premises: (a) that the 105°C accelerated aging test does, in fact, produce at least as much instability as 40 years of central office service will produce and (b) that (2) is an adequate description of the ΔR distribution. Although final confirmation will not be available until about 1990, evidence that these premises are valid is increasing year after year.

It was stated previously that the value of m should not exceed 0.086 *in service* if the resistance variation of not more than one connection in 10,000 is to exceed 0.1 ohm. If the 105°C test is an adequate simulation of service conditions, then those types of connections which have values of m below 0.086 in the 105°C test should be acceptable. This would be the criterion for acceptance if very large samples were tested. Where small samples are tested, however, it is prudent to make allowance for sampling errors.

As stated earlier, the variance of the distribution described by (2) is equal to m. Consequently, the standard deviation of the distribution is equal to the square root of m. If a large number of samples of size N are drawn from a population whose true mean is m', then roughly five per cent of the sample means can be expected to fall below the value

$$m_{0.05} = m' - 1.645\sqrt{\frac{m'}{N}}. \tag{4}$$

A reasonable acceptance level, then, is

$$\begin{aligned} m_{0.05} &= 0.086 - 1.645\sqrt{\frac{0.086}{N}} \\ &= 0.086 - \frac{0.482}{\sqrt{N}}. \end{aligned} \tag{5}$$

In other words, the stability of the connections will be considered acceptable if the mean, m, of a sample of N connections is less than the value of $m_{0.05}$ given by (5). The acceptance level is plotted as a function of N in Fig. 10.

As an aid to decision making, it also is possible to set up a criterion for rejection. If a large number of samples of size N are drawn from a population whose true mean is m', then roughly 95 per cent of the sample means can be expected to fall below the value

$$m_{0.95} = m' + 1.645\sqrt{\frac{m'}{N}}. \tag{6}$$

A reasonable rejection level for the case $m' = 0.086$, then, is

$$m_{0.95} = 0.086 + \frac{0.482}{\sqrt{N}}. \tag{7}$$

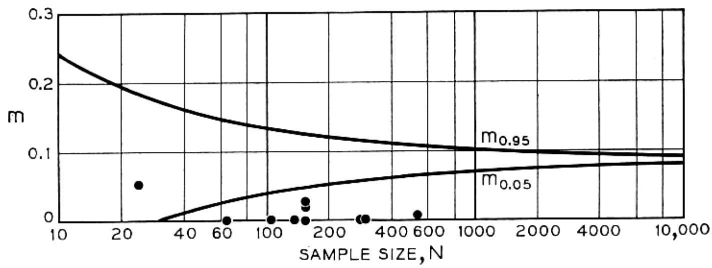


Fig. 10 — Criteria for acceptance and rejection in 105°C accelerated aging test. Points are results of 105°C tests on approved types of solderless wrapped connections.

In other words, the stability of the connections will be considered unacceptable if the mean, m, of a sample of N connections exceeds the value of $m_{0.95}$ given by (7). Further testing of that particular type of connection is not very likely to be profitable, so it might as well be rejected.

Establishing a rejection limit that does not coincide with the acceptance limit provides a zone of uncertainty in which the connections are neither clearly acceptable nor clearly unacceptable. It recognizes the possibility that further testing of a marginal type of connection might demonstrate that the type is acceptable. If the value of being able to approve that type of connection outweighs the cost of further testing, then it may be worthwhile to continue.

On the average, the acceptance criterion of (5) is conservative. Not only does it provide margin for moderate sampling errors, it also provides some margin, on the average, for an error in the basic premise that the 105°C test adequately simulates aging in service.

At the same time, the form of (5) is helpful to the experimenter, for it tells him the minimum sample size that can be used as the basis for acceptance. By setting $m_{0.05}$ equal to zero in (5), the corresponding minimum sample size is found to be 32. If he tests 32 connections and m turns out to be zero, he is entitled to approve the connections without further testing. With a smaller sample, he would not be entitled to approve them even though m turned out to be zero.

From a practical standpoint, it is prudent to test a larger sample when approval is needed in the shortest possible time. If ΔR for even a single connection exceeds 0.001 ohm in a sample of 32, then the connections cannot be approved, the test has to be expanded, and the final decision is delayed. A practical compromise is to test a sample large enough so that four connections could exceed 0.001 ohm slightly without causing m to exceed $m_{0.05}$. If $x = 1$ for the four connections, then $m = 4/N$ and, from (5), the corresponding sample size is 104.

3.4 *175°C Screening Test*

Although the 105°C test appears to be quite effective in distinguishing between stable connections and unstable connections, its slowness is a practical disadvantage. In cases where a number of alternate terminal designs are being considered, for example, and where it is desirable to concentrate development effort on a few of the most promising alternates, the five-month waiting period can be extremely inconvenient. There is need, therefore, for a quick screening test that will serve to identify those types of connections that are likely to pass the 105°C aging test.

Early experience with the 105°C test suggested that addition of mechanical disturbances to the original three-hour undisturbed 175°C test might make it capable of detecting potentially unstable connections. Within limits, this proved to be so.

In the screening test that eventually was standardized, the solderless wrapped connections are baked in an oven for three hours at 175°C. The three-hour period includes the warming up period of the oven and fixtures, which amounts to about one-half hour with the equipment that has been used. During the entire three-hour period, each terminal is plucked automatically once per minute. The plucking mechanism deflects the free end of each terminal $\frac{1}{16}$ inch, then releases it abruptly, allowing the terminal and lead wire to vibrate freely. The opposite end of the terminal is supported rigidly, of course, and the unsupported length (on which the connection is wrapped) is $\frac{19}{32}$ inch.

At the end of the 175°C heat treatment, the connection is cooled to room temperature, and its resistance variation is measured as described previously except that (a) the terminal is plucked only once during the measurement instead of two or three times, and (b) it is plucked $\frac{1}{16}$ inch instead of $\frac{1}{32}$ inch.

In the ordinary cases, where there is no soft solder in the connection, the correlation between the results of this test and the results of the 105°C test has been reasonably good. The principal discrepancy is that the 175°C test is not as sensitive as the 105°C test; that is, the spread between stable and unstable connections tends to be smaller in the 175°C test than in the 105°C test. This can be seen in Table I.

Despite its limitations, the 175°C screening test has been extremely useful in conserving testing effort and in speeding up various phases of the development program. Altogether, more than 16,000 solderless wrapped connections have been subjected to the 175°C test. On a few occasions, final approval of particular types of connections has been based upon results of the 175°C test, although the usual practice is to withhold final approval until the 105°C test is completed.

3.5 *Criterion for Acceptance (175°C Screening Test)*

Empirically, it is possible to define acceptance and rejection limits for the 175°C test that will correspond roughly to the limits for the 105°C test. Although such limits actually have not been used in the past, it appears that limits based upon $m' = 0.22$ for the 175°C test would have led to essentially the same decisions that were made on the basis of 105°C test results. For $m' = 0.22$, the limits for the 175°C test would be

$$m_{0.05} = 0.22 - \frac{0.77}{\sqrt{N}} \tag{8}$$

and

$$m_{0.95} = 0.22 + \frac{0.77}{\sqrt{N}} . \tag{9}$$

These limits are shown in Fig. 11, along with observed values for various types of connections that have been subjected to both the 175°C and the 105°C tests. The symbols used for the values observed in the 175°C test indicate how similar types of connections fared in the 105°C test.

As indicated previously, the limits for the 175°C test can serve as guides for making decisions. If m for a particular type of connection is

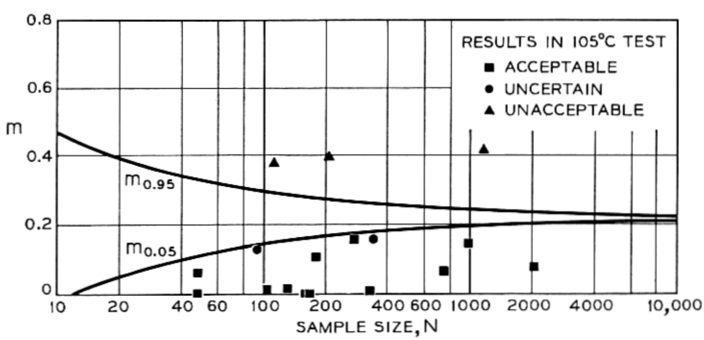


Fig. 11 — Criteria for acceptance and rejection in 175°C screening test. Points are results of 175°C tests, but symbols indicate how similar connections behaved in 105°C tests.

less than $m_{0.05}$, it probably is worthwhile to make tests at 105°C. If m is greater than $m_{0.95}$, it probably is not worthwhile. If m falls between $m_{0.05}$ and $m_{0.95}$, the decision will have to be based upon additional considerations.

The sample size for which $m_{0.05} = 0$ is about 13. The sample size for which $m_{0.05} = 4/N$ is about 41. A sample of 13, then, is the smallest sample that should be tested, and 41 is a more realistic minimum.

IV. MECHANICAL TESTS

Certain standard mechanical tests are made regularly to qualify wrapping bits for use in production, and the same tests have been made to qualify the bits used in the evaluation studies. Sample connections are wrapped on specified types of terminals, then two different types of tests are made on the sample connections. In the first test, the force required to strip the connection off of the terminal is measured. It is required that this stripping force be at least 3000 grams and that the median for any subgroup of five connections be at least 4200 grams. The purpose of this test is to provide assurance that the bit is capable of wrapping tight connections.

In the second test, the wire is unwrapped from the terminal, the unwrapping force being applied to the wire at least one-half inch from the terminal without the wire being restrained from twisting or bending back upon itself. It is required that the connection be capable of being unwrapped in this fashion without the wire breaking. The purpose of this test is to provide assurance that the bit does not wrap too tightly — so tightly that the wire would be weakened excessively.

Assuming that the connections have been wrapped with qualified bits, it is of interest to consider what might happen to them subsequently in service. In general, this reduces to a consideration of mechanical treatments that would tend to loosen the connection and break the wire.

The principal types of mechanical treatment that could loosen a wrapped connection are (a) squeezing the sides of the connection, (b) pushing or pulling on the body of the connection and, of course, (c) unwrapping the connection.

Although the squeezing forces that would be required to loosen connections have not been measured, it is evident that enough force could be exerted with a pair of pliers to damage a connection. Wiremen and maintenance men have been cautioned, therefore, not to squeeze the connections — either with pliers or with test clips.

The force required to slide the connection along the terminal ordi-

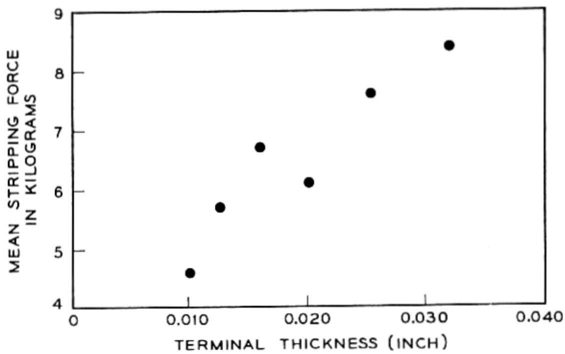


Fig. 12 — Effect of terminal thickness on stripping force. Connections wrapped with No. 24 gauge tinned copper wire on flat nickel silver terminals 0.062 inch wide. Sample size 100.

narily is well above the minimum requirement of 3000 grams, ranging up to more than 10,000 grams in some cases. In general, the heavier terminals tend to give higher stripping forces than do the lighter terminals, and the heavier gauges of wire tend to give higher values than do the lighter gauges. Figs. 12 and 13 illustrate the relationships.

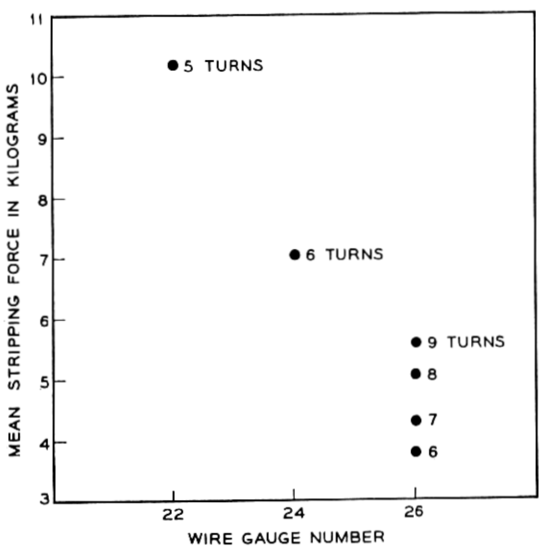


Fig. 13 — Effect of wire size on stripping force. Connections wrapped with tinned copper wire on 0.0319 × 0.062-inch nickel silver terminals. Sample size 50 to 175.

Ordinarily there is little risk that a connection will be unwrapped in normal wiring or maintenance operations — unless, of course, the wire is unwrapped deliberately to remove the connection. It is possible, nevertheless, to unwind a connection by pulling steadily on the lead wire in the direction parallel to, and in line with, the terminal axis. On the average, a force of about 825 grams is sufficient to unwrap one-half turn of a No. 24 gauge connection on a 0.0319 × 0.062-inch terminal, and a force of about 2300 grams will unwrap one full turn. The standard deviations are about 15 per cent of these values.

The principal types of mechanical treatment that are liable to break wires in service are (a) tension alone, (b) repeated bending alone and (c) repeated bending combined with tension. A number of tests have been made to compare the effects of these treatments on wires connected to terminals by solderless wrapping with the effects on wires connected by soldering.

The results of a few tensile tests are summarized in Table II. When the wire was pulled radially (perpendicular to the terminal axis), almost the full breaking strength of the wire was realized with the soldered connections. The breaking strength with the solderless wrapped connections was about eight per cent lower, however, because the wire was indented where it had been wrapped around the corners of the rectangular terminal.

It is interesting to note that, even with soldered connections, the full breaking strength of the wire was not realized when the wire was pulled axially. The soldered joint was broken in stages, and, in most cases, the wire was completely unwrapped from the terminal before the force reached the breaking strength of the wire. With the flat terminals, the ultimate strength of the solderless wrapped connections was significantly lower than that of the soldered connections. With the wire-spring relay terminals, on the other hand, the differences between the solderless wrapped and soldered connections were trivial. The serrations of the

Table II — Mean Ultimate Strength (in Grams) of Connections Made with No. 24 Gauge Copper Wire

Type of Terminal	Direction of Pull on Wire	Solderless Wrapped Connections (6 Turns)	Wrapped and Soldered Connections (1¼ to 2 Turns)
0.0319 × 0.062	Axial	2330	3030
0.0319 × 0.062	Radial	4814	5205
Single Wire	Axial	4450	4444
Twin Wire	Axial	4527	4512

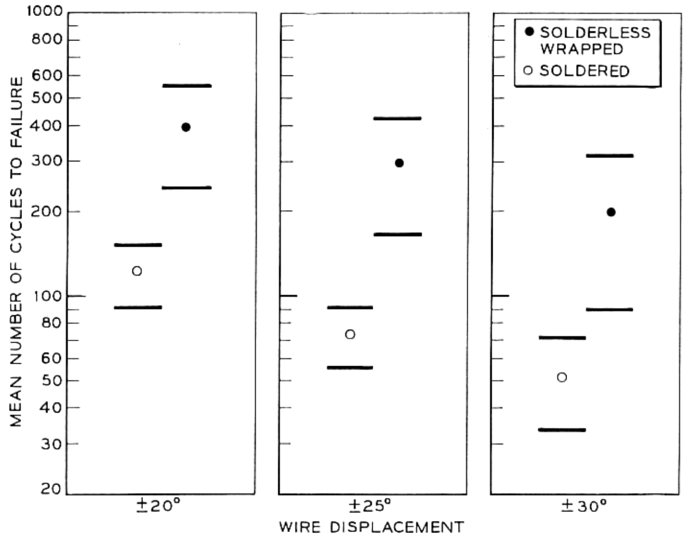


Fig. 14 — Effects of repeated bending without tension. Connections made with No. 24 gauge tinned copper wire on single-wire terminals of wire-spring relay. Sample size 16.

single-wire terminal and the irregularities of the twisted and coined twin-wire terminal were as effective as soldering in locking the wrapped wire in place.

The effects of repeated bending without tension are illustrated in Fig. 14. The test was performed by bending the wire back and forth through the angles indicated until the wire broke. The bending moments were large enough to exceed the elastic limit of the copper wire. In Fig. 14 conventional $\pm 3\sigma$ control limits (or confidence limits) are shown with each plotted point as a simple, graphic way of indicating that the performance of the solderless wrapped connections was significantly better, on the average, than that of the soldered connections.

Vibration tests, of course, provide another method for measuring the effects of repeated bending without tension. Fig. 15 shows the results of a vibration test performed by the Western Electric Company on small equipment units wired with local cables. The $\pm 3\sigma$ control limits in this case are based upon the observed breakage ("fraction defective") of the soldered wires. The fact that the observed breakage of the solderless wrapped wires consistently fell below the lower control limit for the soldered wires indicates that the performance of the solderless wrapped wires was superior on the average.

The effects of repeated bending combined with tension are shown in Fig. 16. In this test, the wire was kept under tension continuously while it was bent from its starting position perpendicular to the terminal axis to a second position parallel to the terminal axis and then back to its starting position. This cycle was repeated, always in the same direction from the starting position, until the wire broke. In Fig. 16, the $\pm 3\sigma$ control limits indicate again that the performance of the solderless wrapped wires was better, on the average, than the performance of the soldered wires.

From the results of tests such as those which have been described, it has been concluded that the solderless wrapped connection satisfies the mechanical security objectives in part, but not completely. It is more vulnerable to loosening by axial pull on the wire than is the soldered connection, so this limitation should be recognized in authorizing applications of solderless wrapping. In its ability to withstand vibration and repeated bending of the lead wire, however, the solderless wrapped connection appears to be fully as good as, and probably better than, the soldered connection.

V. APPROVED COMBINATIONS OF TERMINALS AND WIRE

Present approvals of specific combinations of terminals and wire are based very largely upon the results of the accelerated aging tests that

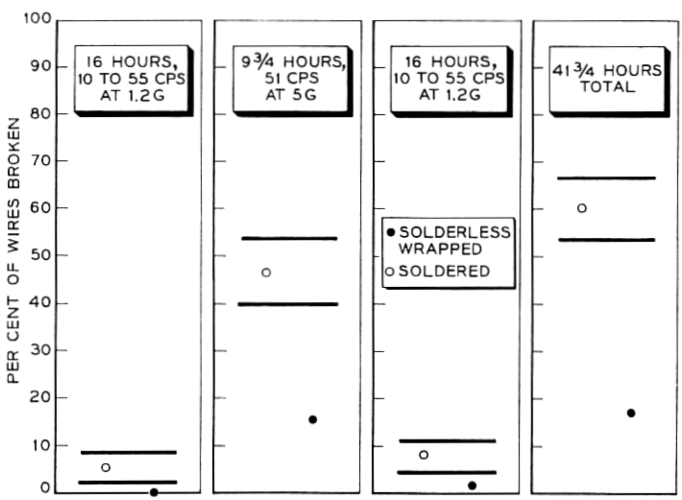


Fig. 15 — Results of vibration test on small equipment unit wired with local cable. Sample size 550 for each type of connection.

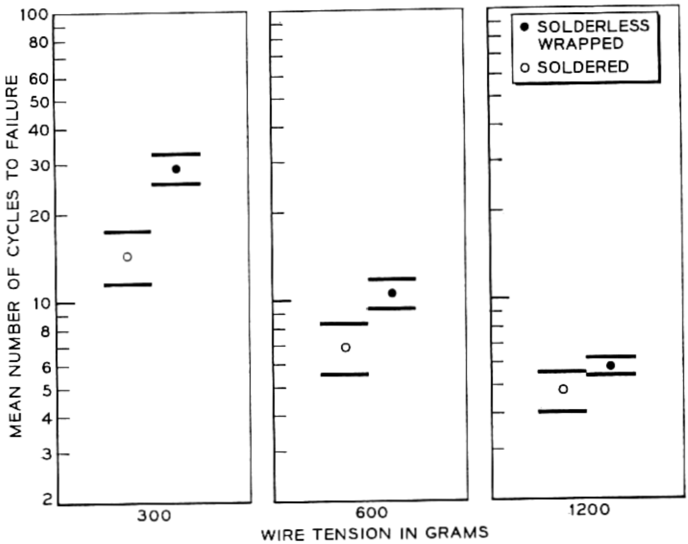


Fig. 16 — Effects of repeated bending with wire under tension. Connections made with No. 24 gauge wire on single-wire terminals of wire-spring relay. Sample size 25 in each case.

have been described, upon the ability of the manufacturer to manufacture the terminals economically and upon a limiting dimension of a wrapping bit that is used widely.

The limiting dimension is the minimum diameter of the terminal hole in the bit used for wrapping No. 24 gauge wire. In order to be sure that No. 24 gauge wire can be wrapped on any approved terminal, the maximum dimensions of the cross-section are limited so that the terminal will pass through a circular opening 0.073 inch in diameter.

Solderless wrapping with No. 22 gauge tinned copper wire is approved on terminals of rectangular cross section whose nominal thickness is at least 0.030 inch and whose minimum diagonal exceeds 0.061 inch.

Solderless wrapping with No. 24 gauge tinned copper wire is approved on (a) terminals of rectangular cross section whose nominal thickness is at least 0.025 inch and whose minimum diagonal exceeds 0.059 inch, (b) embossed terminals of the form shown in Fig. 6 punched and formed from flat stock whose nominal thickness is at least 0.010 but less than 0.025 inch and (c) the wire-spring relay terminals in Figs. 7 and 8.

Approved terminal materials include nickel silver, brass, phosphor bronze and silicon copper. The best terminal materials for solderless wrapping have a high modulus of elasticity, a low rate of stress relaxation and a temperature coefficient of expansion near that of the wire.

In general, a copper flash plus an electrotinned finish is required on brass, phosphor bronze and silicon copper terminals, or they may be punched from either tin-coated or solder-coated stock. No finish is required on nickel silver terminals, although any of the foregoing finishes is permissible and is specified in some cases to facilitate soldering. Solder dipping is not approved, because of the risk of obtaining abnormally thick coatings from time to time and the undesirable effect that this could have upon the stability of connections wrapped on such terminals.

The use of untinned copper wire has been approved only in cases where the required service life of the connections is substantially less than 40 years. Furthermore, such approvals are limited to the heavy terminals which are approved for use with No. 22 gauge wire.

There have been exceptions to some of the standards described in the preceding paragraphs. Solderless wrapping on solder-dipped terminals and on thin, flat terminals was approved on a limited basis early in the development program. Those connections, however, are in circuits where trouble, if it should occur, would be detected automatically, could be located quickly and could be corrected easily by soldering the defective connection. For future production, those terminals are being brought into agreement with present standards.

VI. PERFORMANCE IN SERVICE

The first field trial of solderless wrapped connections was installed in 1950, and limited use of solderless wrapping in regular manufacture began a few years later. During the period 1950 to 1958, the service performance of solderless wrapped connections appears to have been highly satisfactory.

A two-year survey of 411,000 solderless wrapped connections in five central offices showed a lower wire breakage rate than would have been expected with soldered connections, and the difference was great enough to be considered statistically significant.

There has been no report of solderless connections being pulled off of terminals in service or of being partially unwrapped, and inspection of about 20,000 connections in two central offices revealed no sign of partial unwrapping.

The resistance variations of 135 connections were measured after two years in service, and 160 more were measured after three and one-half years of service. The highest value of ΔR observed was 0.0004 ohm, so the value of m for the 295 connections still was zero.

VII. CONCLUSION

The laboratory studies and field experience to date have provided considerable assurance that properly designed and properly made solderless wrapped connections will perform satisfactorily for 40 years in central office service. The use of solderless wrapping is being expanded, therefore, in the Bell System. Suitable terminals now are being provided on many types of telephone apparatus. Design changes have been authorized to provide suitable terminals on a number of additional types of apparatus, although the changes have not been introduced yet in manufacture. And design changes to provide suitable terminals on still other types of apparatus are being studied.

Several hundred million solderless connections are being wrapped each year in the Bell System now. The number will grow, but it is difficult to predict what the saturation level will be. Inevitably, the solderless wrapped connection is in competition with soldered connections, clinched connections, welded connections and all the other types. In the end, the choice of connections for any particular application is likely to be an economic choice — based not only upon the cost of the labor involved in making a connection, but upon many other factors as well. The cost of modifying terminals, for example, is an obstacle to solderless wrapping on existing apparatus. In some cases, the cost of modifying the terminals of a particular type of apparatus outweighs the potential savings of solderless wrapping. It is not likely, therefore, that solderless wrapping ever will displace other types of connections completely.

The present program for central office equipment in the Bell System calls for modification of the terminals of existing types of apparatus in those cases where the preparation expense clearly is outweighed by the direct savings from solderless wrapping and the indirect savings from the use of plastic insulated wire, which is made practicable by solderless wrapping. In other cases, modification of terminals will be deferred until present manufacturing tools wear out and have to be replaced.

In designing new types of apparatus — especially switching apparatus — the trend is to provide terminals suitable for solderless wrapping at the start. Furthermore, every effort is made to arrange the terminals in modular arrays that will facilitate automatic wiring by machines. These two steps are opening a door to economical use of automatic wiring in manufacture. It seems quite probable, therefore, that telephone switching systems of tomorrow will be well populated with solderless wrapped connections.

VIII. ACKNOWLEDGMENTS

Many persons, working in several closely knit teams, have participated in the development of solderless wrapped connections. Each of those persons has played an important part in the development. In particular, the author wishes to acknowledge the contributions of H. L. Coyne and R. H. Van Horn, who supervised the several phases of the evaluation program.

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