A Comparison of Permanent Electrical Connections

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A study has been completed which compares four types of permanent electrical connections (soldered, solderless wrapped, percussive welded, and resistance welded) under environmental conditions of vibration, shock, temperature extremes, corrosion, humidity, and bending. Only good-quality connections were included in this study, and they represented the current state-of-the-art for each type. Under these conditions the connections showed no significant degradation in their electrical characteristics as long as they remained mechanically secure. Differences in the four types of connections were therefore assessed in relation to their mechanical characteristics. Consequently, one of the more important results of the study was the recognition of fatigue life as the most important mechanical connection characteristic when comparing connections which meet the high standards of the Bell System for electrical stability. Using fatigue life as a basis for comparison and soldered connections as a reference standard, the major conclusions with regard to general wiring (the connection of wires to terminals, such as surface and local cable wiring) are as follows for the conditions that existed in this study:

(a) monitored percussive welded connections are superior to soldered connections;

(b) over-all, solderless wrapped connections are essentially equivalent to soldered connections;

(c) resistance welded connections are significantly inferior to soldered connections.

Although differences were found among the types of connections, no evidence was obtained that any of the connection types are not satisfactory as presently used in normal Bell System applications.

I. INTRODUCTION

The Bell System uses many types of electrical connections. The best connection for a specific application is chosen on the basis of the relative merits of the connections in the following general areas:

(1) adaptability of each connection for the application under consideration,

(2) reliability or life required from the connections under the environmental conditions in which the equipment must operate, and

(3) relative cost of each connection.

This study was concerned with obtaining information on the comparative reliability or life of the four main types of permanent connections (solderless wrapped, soldered, percussive welded, and resistance welded) under various environmental conditions. The probability of the occurrence of substandard connections was recognized as a factor in determining the reliability of a given type of connection. However, only good-quality connections of each type were compared in this study, and all present manufacturing standards were followed in making them.

All four types of connections are considered adequate for the applications in which they are presently used, and the results of this study should not be construed as a recommendation to change to a different type of connection in these applications.

The scope of the program is illustrated by Fig. 1. It shows general wiring application (the connection of wires to terminals such as surface and local cable wiring) and the environments considered.

Some of the environments chosen are more severe than those normally encountered in a central office. This was necessary to produce a measurable effect in a reasonable time and should not alter the results, because this was a comparison study.

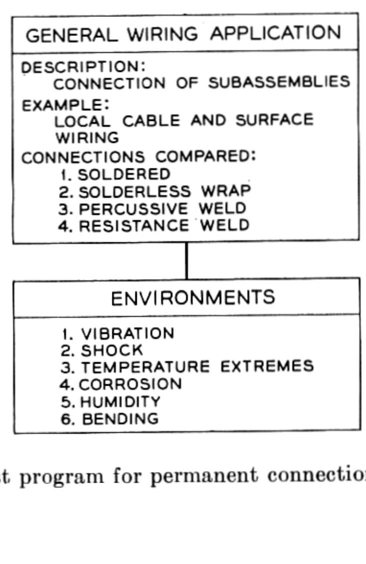

Fig. 1 — Test program for permanent connection comparison.

The end result from each of the environmental tests was the establishment of an "order of merit" for the four types of connections in that particular environment. Thus the connection which suffered the least degradation in an environment would be placed at the top of the "order of merit" list and the connection which showed the greatest degradation would be on the bottom.

Early in the test program, it was observed that none of the test environments caused any electrical failures and that very few of the test environments caused mechanical connection failures. Thus, it was concluded that the establishment of an "order of merit" would have to be obtained from some observed mechanical degradation in destructive tests. Two types of tests always led to connection failure, i.e., breakage, and these were the vibration and bending fatigue tests. The establishment of an "order of merit" for these tests was very simple: the connections which lasted the longest were the best and those which failed first were the poorest.

Since both of these tests are essentially fatigue tests, it was realized that the fatigue life of a connection could be a better basis of comparison than an ultimate-strength test, since all the test connections had met the rigid Bell System standards for electrical stability. Further analysis, as described in Section 3.1, led to the conclusion that fatigue life should be used as the comparison basis throughout this study for the following reasons:

(1) A comparison based on fatigue life offers an absolute comparison scale for the types of connections studied.

(2) Electrically stable permanent connections can be characterized by their fatigue life.

II. TEST PROCEDURES AND RESULTS

2.1 *General*

The quality and uniformity of each group of connections was determined by destructively testing approximately half the group and thus establishing the strength distribution of the remaining half, or test connections. The destructively tested or control connections were generally selected alternately by order of manufacture, from the whole group of connections. The destructive strength control data are presented in the Appendix along with a description of the destructive strength method used for each type of connection.

Because of the statistical nature of the data collected in a program of this type it is necessary to present the data in the form of probability distributions, as shown in Fig. 2. The ends of the bar represent the 10 per cent and 90 per cent points on the distribution and the projecting line between represents the 50 per cent point.

2.2 *Environmental Tests*

Typical examples of the four types of connections compared in this study are shown in Fig. 3. Since this study is basically a comparison of the four types of connections, every effort was made to hold all of the unknown parameters to an absolute minimum, and this was accomplished to a great extent by subjecting all of the connections to the same environment at the same time. The connections were mounted on fixtures to facilitate the handling and the mounting during exposure to the various environments. These mountings were of two types, as shown in Fig. 4: (a) connections with insulation, consisting of 3-inch loops of wire connecting two terminals, the group thus containing forty connections, i.e., 20 loops of wire; (b) connections without insulation, the wire having a 90° bend near the terminal and being fastened directly to a standoff insulator. This last type was designed for the resistance change measurements (ΔR) which were required for the temperature, corrosion and humidity test environments.

This study consisted of the sixteen general wiring tests listed in Table I. Most of these were of the comparison type, but a few were studies concerned with only one type of connection. All of the vibration fatigue

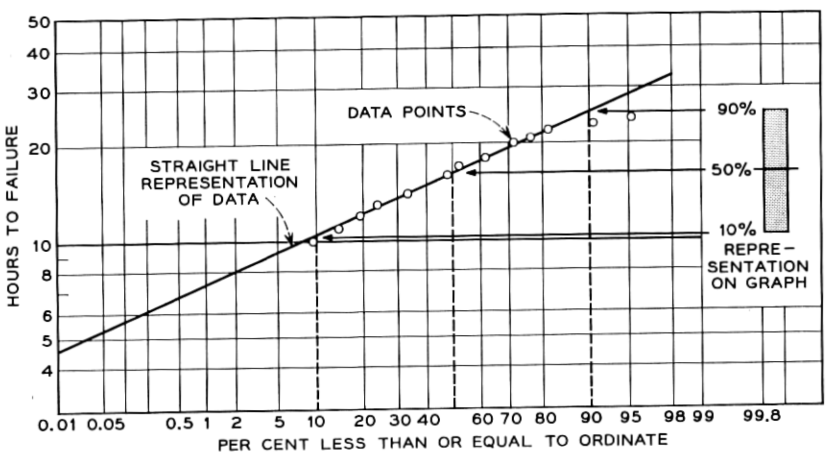

Fig. 2 — Typical test data.

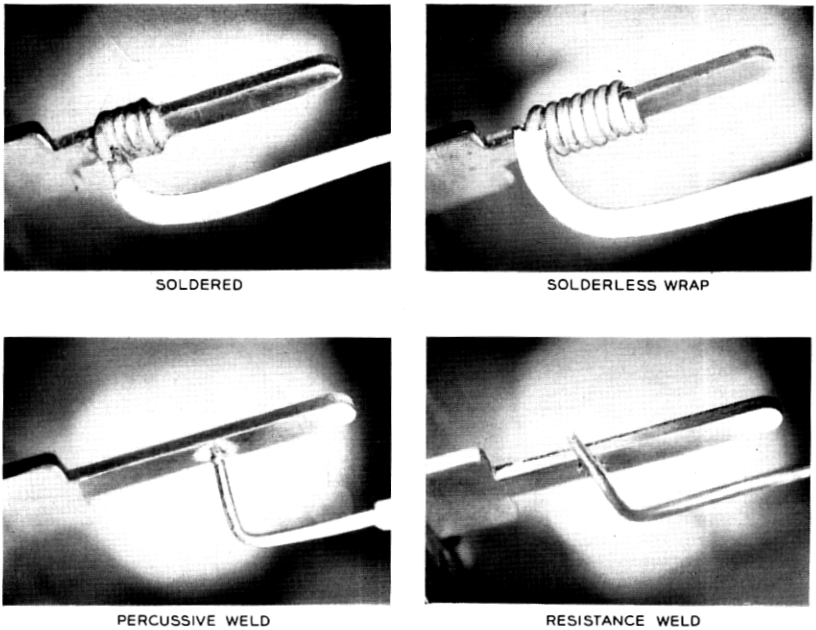

Fig. 3 — Typical examples of general wiring connections.

tests, with the exception of test 14, used the vibration configuration shown in Fig. 5.

The first footnote of Table I requires some explanation. The vibration fatigue life determinations in this study were spread over a considerable number of months because of the long exposure times for some of the

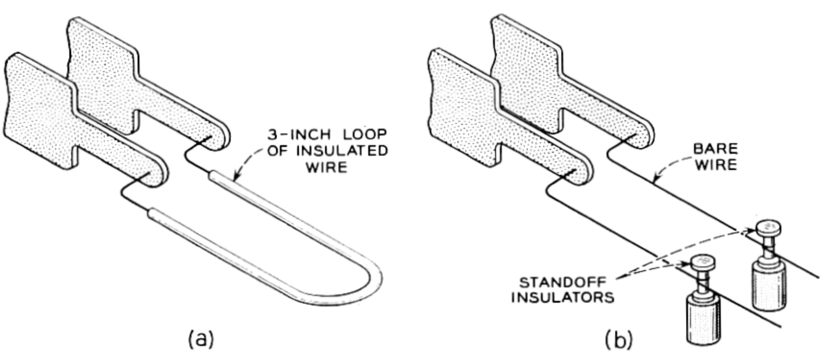

Fig. 4 — Typical general wiring connections: (a) with insulation, (b) without insulation.

TABLE I — LIST OF GENERAL WIRING TESTS

Test Description	Test Number	Insulation		Fatigue Method			Number of Connections of Each Type Tested	Figure Number of Results
		Without	With	Vibration	Lightly Loaded Bending	Heavily Loaded Bending		
Vibration test without insulation	1	X		X			80	6
Vibration test with insulation	2		X	X			40	6
Shock test, laboratory (fatigue life)	3		X	X			40	7
Shock test, laboratory (destructive test)	4		X				40	8
Shock test, railroad non-cushioned	5*		X	X			20	9
Shock test, railroad cushioned	6*		X	X			20	9
Temperature test, central office conditions	7	X		X			40	10
Temperature test, outside plant conditions	8	X		X			40	10
Three months corrosion test	9	X		X			20	11
Six months corrosion test	10*	X		X			20	11
Humidity test	11	X		X			40	12
Lightly loaded bending test (30° angular displacement)	12		X		X		40	14
Heavily loaded bending test (45° angular displacement)	13		X			X	40	16
Configuration test	14		X	X			40	17
Ultimate strength as a function of fatigue life	15	X			X		120†	18
Inferior weld test	16	X			X		20†	19

* Test conducted after recalibration of the vibration machine.
† Only percussive welded connections tested.

tests. Toward the end of the testing, the mounting springs on the table of the vibration machine had to be replaced and the machine recalibrated. This recalibration seems to have affected the fatigue life determination of some or all of the subsequent tests; however, it has not been possible to determine the extent of this difference or even to prove that

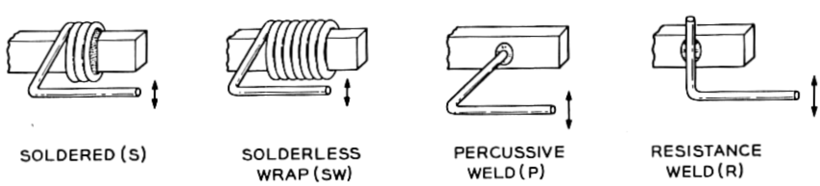

Fig. 5 — Standard vibration configuration.

it does or does not exist. If a difference does exist, it would introduce an error in the comparisons between the vibration fatigue life data of some of the later tests and the control fatigue life data (test 1 or 2) but would not affect the comparison among the four types of connections on a particular test, since they all experienced the same vibration environment.

2.2.1 *Vibration Tests*

The vibration tests have been divided into two general classifications: (a) those for wires without insulation and (b) those for wires with insulation.

The results of these two tests are shown in Fig. 6, and they cover the fatigue life of the four types of connections, with and without insulation. The connections which were connected with a loop were grouped in pairs. They were vibrated according to the schedule listed in Table II and used the vibration configuration illustrated in Fig. 5. The actual motion of the wires was a function of the mass of the loop as well as the acceleration of the connection; therefore all loops were made as close to the same size as possible.

In test 1 (without insulation) it was necessary to solder loops on the connections, since these were set up for resistance change (ΔR) measurements as shown in Fig. 4(b) and therefore had no loops. Care was taken to control the size and weight of these loops so that they would closely approximate the loops with insulation in test 2, shown in Fig. 4(a).

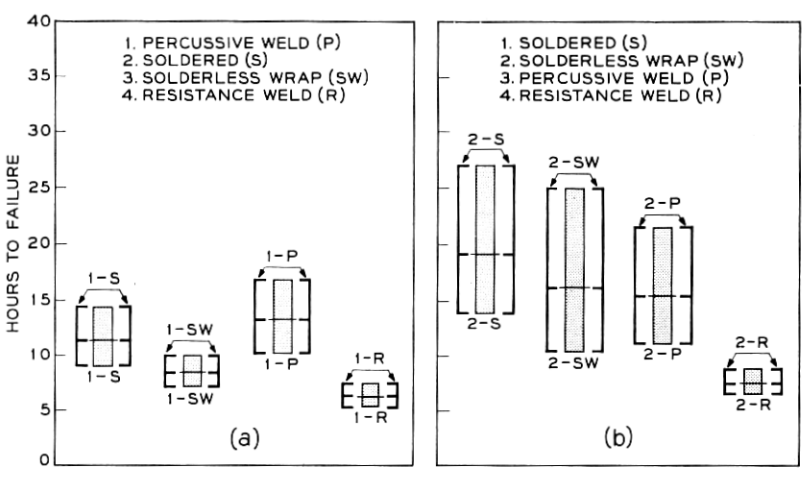

Fig. 6 — Vibration fatigue life results. (a) Test number 1 (without insulation); order of merit, based on vibration fatigue life. (b) Test number 2 (with insulation); order of merit, based on vibration fatigue life.

TABLE II — VIBRATION SCHEDULE

The vibration was sinusoidal in wave shape and its frequency varied from 5 cps to 500 cps and back to 5 cps in 2 minutes. The displacement, acceleration, and running time schedules were as follows:

Displacement (Inches)	Acceleration (G's)	Running Time (Hours)
0.1	5	2
0.2	10	2
0.3	15	2
0.4	20	2
0.5	25	to destruction

Note: The cross-over frequency was approximately 30 cps: that is, 5 to 30 cps controlled displacement and 30 to 500 cps controlled acceleration.

Since the connections were grouped in pairs and the weakest connection of the pair failed first, no usable fatigue data could be obtained from the remaining connection and it was clipped off, leaving a stub which could be destructively tested.

2.2.2 *Shock Tests*

The shock tests can be divided into two general classifications: (a) laboratory shock and (b) railroad shock. Two laboratory shock tests were conducted, one using the vibration fatigue life after the shock test as a measure of the connection degradation, and the other using the destructive strength as an indication of any degradation suffered by the connections. These tests consisted of subjecting all four types of connections to 90 high-level shocks. All of the shock test connections were mounted on a fixture and experienced the same shocks at the same time. Half sine wave shocks were used with a peak amplitude of 500 to 600 G's and a duration of 2 to 3 milliseconds. There were no connection failures due to this shock environment. In the case of the fatigue life part, test 3, the connections were then subjected to the vibration schedule (Table II) and their fatigue life determined. The results of these tests are presented in Fig. 7.

In the case of the destructive strength part, test 4, the connections were destructively tested after the 90 shocks, each in accordance with the method prescribed for it, as described in the Appendix. The results of these tests are compared to a destructive strength control and are shown in Fig. 8.

It should be noted that the order of merit for test 4 could not be based on any absolute strength scale because of the differences in the destruc-

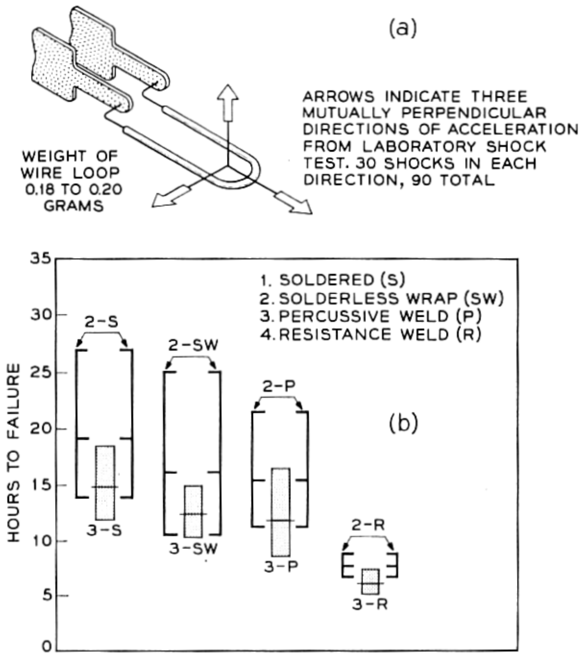

Fig. 7 — Vibration fatigue life after laboratory shock tests. (a) Typical connection orientation during shock tests. (b) Test number 3 (with insulation); order of merit, based on vibration fatigue life.

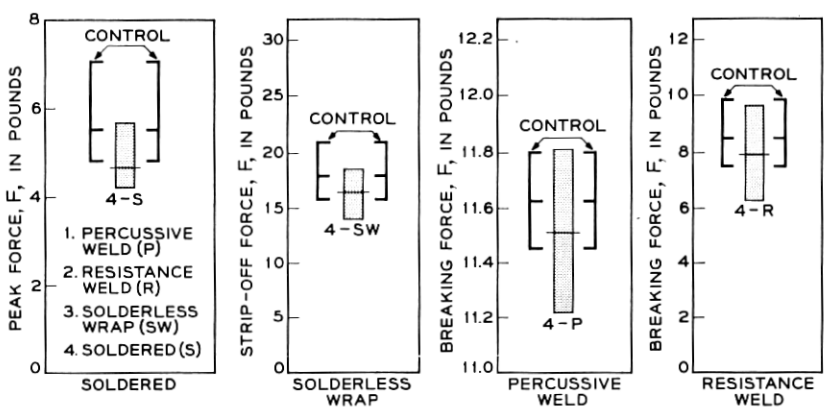

Fig. 8 — Destructive strength after laboratory shock tests (test number 4); order of merit, based on percentage of destructive test degradation.

tive strength tests. It was therefore based on the percentage degradation indicated by the difference between the mean of the control sample and the mean of the sample which had been exposed to the shock.

The railroad shock tests were of two types: (a) noncushioned, test 5, and (b) cushioned, test 6. These tests consisted of sending the four types of connections in a rigid plywood box from Columbus, Ohio, to New York City by railway express for a total of ten round trips. The connections from both tests, numbers 5 and 6, were shipped in the same container; however, the noncushioned connections were fastened directly to the plywood box, whereas the cushioned connections were supported by rubberized hair in the center of the container. The fatigue life of the connections was determined after the ten round trips by vibrating them according to the vibration schedule (Table II). The results of both tests are presented in Fig. 9. There was very little difference in degradation observed for the two tests, and they resulted in identical orders of merit based on the vibration fatigue life.

The vibration fatigue life determination for these two tests was conducted after recalibration of the vibration machine as discussed in Section 2.2, and this could affect the comparison between these tests and the control; however, it will not affect the comparison of each type of connection within tests 5 and 6.

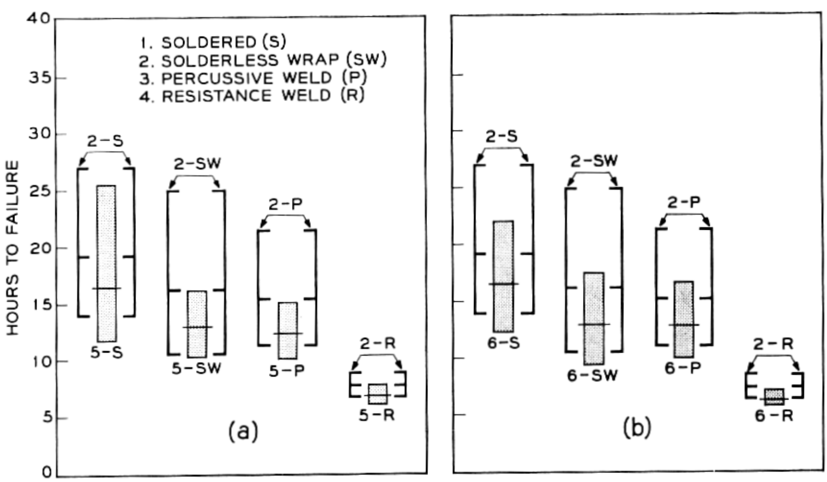

Fig. 9 — Vibration fatigue life after railroad shock and vibration. (a) Test number 5 (noncushioned); (b) test number 6 (cushioned). The order of merit, based on vibration fatigue life, was the same for both tests.

2.2.3 *Temperature Tests*

The connections were subjected to two types of temperature tests: (a) central office conditions, test 7, and (b) outside plant conditions, test 8.

The central office temperature test consisted of subjecting forty connections of each type to a temperature of 105°C for a total of 154 days. Once a week the connections were removed from the oven and allowed to come to room temperature (20°C). Every two weeks the connections were mechanically disturbed (plucked) and the change in resistance, ΔR, was measured. After the 154 days, loops were carefully soldered to the connections and they were subjected to vibration according to the vibration schedule (Table II) and their fatigue life determined. The results are presented in Fig. 10. All forty connections of each type survived the 154-day test without developing a change in resistance, ΔR, of 0.001 ohm, which would have constituted an electrical failure. The solderless wrap connections, however, did develop a considerably higher number of ΔR's, as shown in Table III.

The soldered, solderless wrap, and resistance welded connections showed a small but significant loss in fatigue life due to test 7. The percussive welded connections, however, showed a larger, more significant loss in fatigue life due to the temperature test.

The outside plant temperature test, test 8, was very similar to the central office condition temperature test. The differences were that test 8 ran for 168 days and that when the connections were removed from the

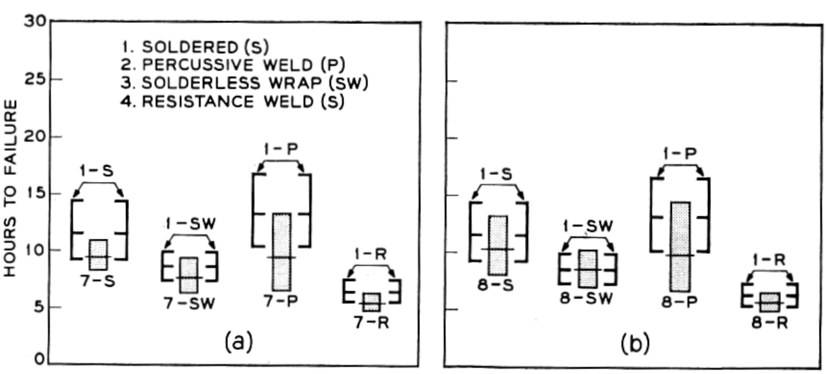

Fig. 10 — Vibration fatigue life after temperature tests. (a) Test number 7 (central office conditions); (b) test number 8 (outside plant conditions). The order of merit, based on vibration fatigue life, was the same for both tests.

TABLE III — NUMBER OF ΔR VALUES OBSERVED FOR EACH TYPE OF CONNECTION

ΔR Values in Milliohms	Soldered		Solderless Wrap		Percussive Weld		Resistance Weld	
	CO	OP	CO	OP	CO	OP	CO	OP
0.2	6	none	42	44	1	1	3	1
0.3	none	none	8	9	none	none	none	none
0.4	none	none	1	2	none	none	none	none
0.5	none	none	4	1	none	none	none	none
0.6	none	none	none	1	none	none	none	none

Note: CO = central office conditions, OP = outside plant conditions.

oven at 105°C they were immediately placed in a cold box at −40°C and allowed to stabilize at this temperature. After approximately an hour at −40°C, they were removed and allowed to come to room temperature (20°C). Resistance change data and vibration fatigue life information were obtained in the same manner as the central office temperature test; the results are presented in Table III and Fig. 10. The changes in resistance and fatigue life data for the outside plant conditions were similar to the results obtained from the central office conditions, except that the soldered and solderless wrapped connections sustained less degradation. Both temperature tests yielded the same order of merit.

2.2.4 *Corrosion Tests*

The corrosion tests were of two types: (a) three months, test 9, and (b) six months, test 10. These tests were identical in all respects with the exception of the exposure time, as indicated in Fig. 11. They consisted of exposing all four types of connections to the corrosive atmosphere of New York City on the roof of the Bell Laboratories building at West Street. Resistance change measurements were made on all of the connections before and after exposure. All corrosion test connections survived the environment without developing the 0.001-ohm resistance change which would have constituted an electrical failure.

The apparent increase in fatigue life of all the connections, except for percussive welded connections, in the six months corrosion test is unexplainable except for the recalibration of the vibration machine discussed in Section 2.2. This is the most probable cause of this inconsistency, since there is no reason to expect that exposure to a corrosive atmosphere can improve the fatigue life of any type of connection.

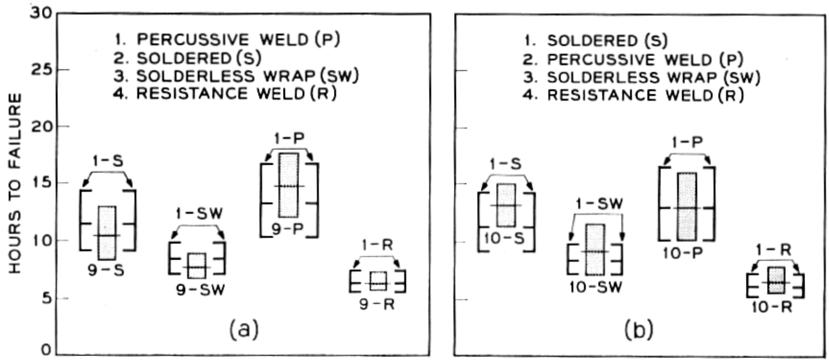

Fig. 11 — Vibration fatigue life and orders of merit after corrosion tests. (a) Test number 9 (three months); (b) test number 10 (six months).

2.2.5 *Humidity Test*

The humidity test, test 11, consisted of subjecting all four types of connections to controlled temperature and humidity conditions according to the following schedule: they were exposed to 90 per cent relative humidity and 85°F dry bulb temperature for six consecutive days, then dried at 140°F for two days. This cycle was repeated eight times for a total test time of 64 days. Resistance change measurements were made before, during, and after the test with no electrical failures being observed. The fatigue life of the connections was determined by carefully soldering loops of wire to the connections and vibrating them according to the vibration schedule (Table II). The results are presented in Fig. 12.

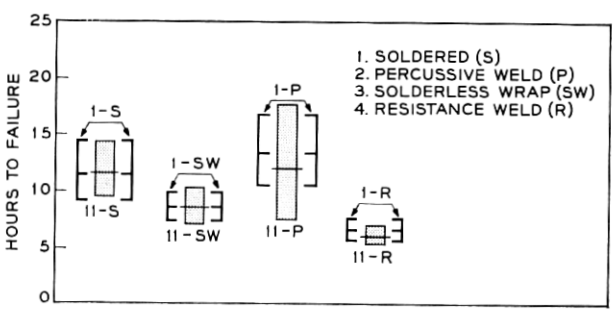

Fig. 12 — Vibration fatigue life and order of merit after humidity test, test number 11.

2.2.6 *Bending Tests*

All four types of connections were subjected to two bending tests: (a) the lightly loaded bending test, test 12, and (b) the heavily loaded bending test, test 13.

Bending, in the lightly loaded bending test, took place in a horizontal plane as shown in Fig. 13. The load on the connections came from the tension in the wire and varied from approximately 0 to 4 grams. The wire was moved 30° in one direction from its equilibrium position and then returned, and then moved 30° in the other direction and returned to its equilibrium position. This constituted one cycle. The number of such cycles to failure for each connection was the fatigue data. Forty connections of each type were tested and the results are presented in Fig. 14.

The heavily loaded bending test consisted of determining the bending fatigue life of all four types of connections by bending in a vertical plane with 300 grams hanging on the connection, as shown in Fig. 15. At a relatively slow rate the terminal was rotated 45° from its originally horizontal position and then returned. This constituted one cycle. The number of such cycles required to cause failure of each connection was the fatigue data. Forty connections of each type were tested for all connections except solderless wrap, of which 32 were tested; results are presented in Fig. 16.

2.2.7 *Additional Tests*

There were three additional tests conducted in this study; (a) configuration test, test 14, (b) ultimate strength as a function of bending fatigue life for percussive welded connections, test 15, and (c) inferior weld test, test 16.

The configuration test consisted of determining the vibration fatigue life of the four types of connections, using a different configuration. The 90° bend used in the configuration shown in Fig. 5 was eliminated and the wire was brought straight from the terminal as shown in Fig. 17(b). Vi-

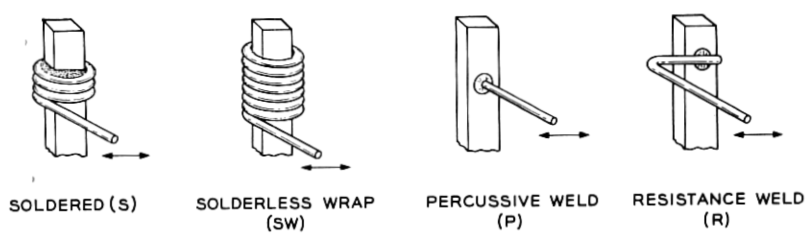

Fig. 13 — Lightly loaded bending configurations.

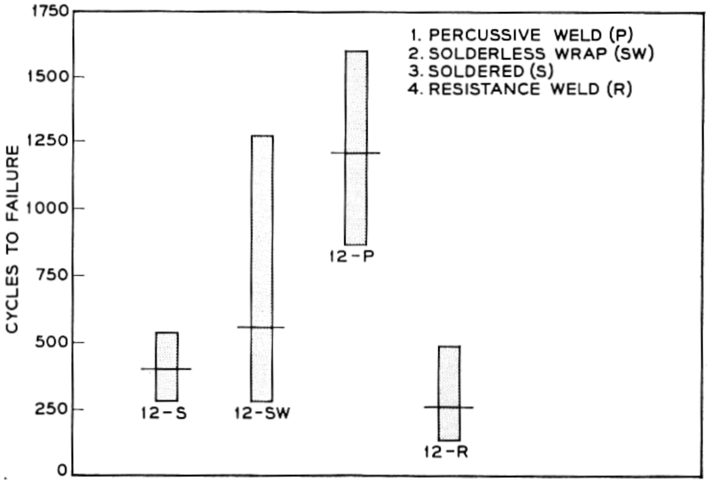

Fig. 14 — Lightly loaded bending fatigue life, test number 12 (with insulation); order of merit, based on bending fatigue life.

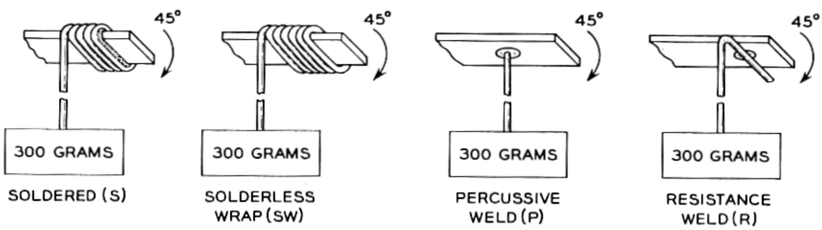

Fig. 15 — Heavily loaded bending configurations.

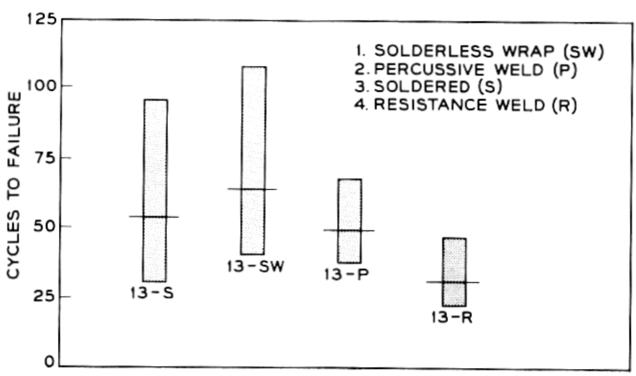

Fig. 16 — Heavily loaded bending fatigue life, test number 13 (with insulation); order of merit, based on bending fatigue life.

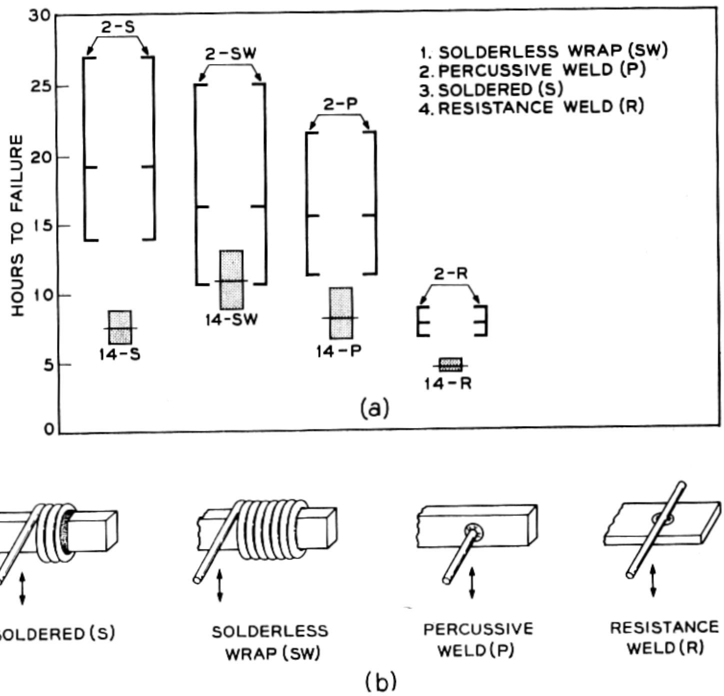

Fig. 17 — (*a*) Vibration fatigue life with configuration omitting 90° bend in the lead-off wire, test number 14 (with insulation); order of merit, based on vibration fatigue life. (*b*) Vibration configuration omitting 90° bend.

bration still took place in a vertical plane and the vibration schedule (Table II) was followed. The results of this test are also shown in Fig. 17(a). All four types of connections showed a deterioration in their fatigue life when the 90° bend was omitted. This bend apparently partially isolates the connections from external wire movements and therefore improves their fatigue life.

The objective of test 15 was to determine the ultimate strength of percussive welded connections as a function of the bending fatigue life. The fatigue method selected was the lightly loaded bending type. A total of 240 percussive welded connections were used in this test; they were divided into two groups of 120 each. The first group was destructively tested immediately after manufacture to determine their strength, and these data are included in the destructive strength control presented in the Appendix. The remaining 120 connections were divided into eleven groups: one group of 20 connections and 10 groups of 10 connections

TABLE IV — SCHEDULE FOR TEST 15

Number of lightly loaded bending cycles	500	600	700	800	900	1000	1100	1200	1300	1400
Surviving connections	10	10	9	10	9	9	7	3	6	2
Average strength of surviving connections in pounds	11.1	11.1	11.1	11.2	10.8	10.9	11.1	10.7	10.5	10.7

each. The 20-connection group was fatigued to failure by the lightly loaded bending method to establish the fatigue life of the connections. The other ten groups were each fatigued to a predetermined number of bending cycles according to the schedule shown in Table IV. After the connections in each group had been fatigued for the number of cycles assigned to that group, the connections remaining were destructively tested using the combined test.

The results of this test, presented in Fig. 18, indicate that at 100 per cent of the average fatigue life the surviving connections show only an approximate 5 per cent reduction in their ultimate strength. This indicates that the mechanical quality of a percussive welded connection is characterized better by its fatigue life than by its ultimate strength.

The object of the inferior weld test, test 16, was to determine the ultimate strength and fatigue life of inferior percussive welds and to compare these characteristics with those of good welds. The welds were made inferior by using insufficient capacitance in the welding power supply during their manufacture. The results are presented in Fig. 19. The

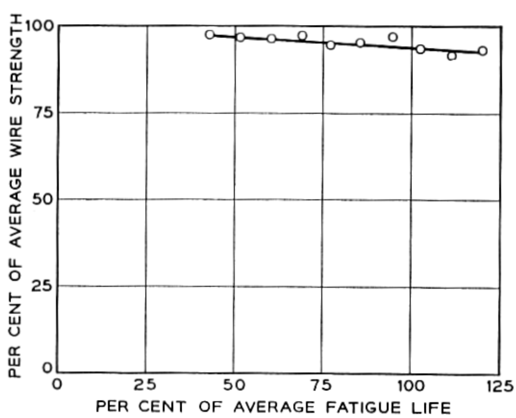

Fig. 18 — Ultimate strength as a function of bending fatigue life for percussive welded connections, test number 15 (without insulation).

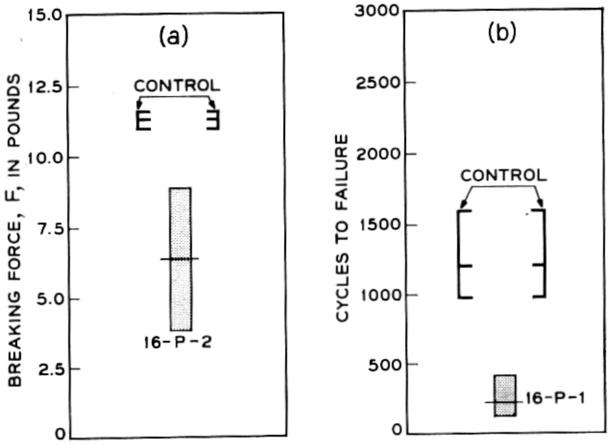

Fig. 19 — Inferior weld test, test number 16: (a) destructive strength — inferior welds show 55 per cent of the strength of good welds, based on the means of the distributions; (b) bending fatigue life (without insulation, lightly loaded bending) — inferior welds show 17 per cent of the bending fatigue life of good connections, based on the means of the distributions.

combined destructive test was used to determine the ultimate strength of the connections, and the fatigue method selected was of the lightly loaded bending type.

The welds used in this test showed only 55 per cent of the strength of good connections, and the fatigue life of the inferior type welds showed 17 per cent of the fatigue life of good connections. These results indicate that, for percussive welding, bending fatigue life is a much more sensitive indicator of weld quality than the strength of the connection as measured by the destructive combined test.

III. DISCUSSION

3.1 *Importance of Fatigue*

The measure of life expectancy chosen for this study was the fatigue life of the connections. The effect of the various nondestructive environments was measured by determining the loss of fatigue life caused by them. During testing, no significant electrical degradation was observed on any of the test connections as long as they remained mechanically secure. Comparison of the four types of connections was therefore made on the basis of their mechanical characteristics. Fatigue life was found to be the most important mechanical characteristic of permanent electrical connections, as well as being one of the most sensitive indicators of connection degradation.

Fatigue life was measured in both vibration and bending. The vibration fatigue life was measured by the number of hours the connections survived a specified vibration schedule, and the bending fatigue life was measured by the number of cycles to failure of the connections in the lightly loaded and heavily loaded bending configurations. A comparison based on fatigue life offers an absolute comparison scale for all types of connections and facilitates the determination of an order of merit.

A given connection is better than another if, under identical environmental conditions, its life is longer. The life of a connection has ended when for any reason it fails to provide an adequate path for electrical current. In general, a connection may fail in two ways, electrically or mechanically. An electrical failure occurs when the connection develops an electrical characteristic such as a large constant or variable resistance which is incompatible with the equipment in which it is used. This type of failure is generally important only for pressure type connections; with properly designed and applied connections of this type it poses no serious threat to long life.

A mechanical connection failure occurs when the conducting path is physically broken. Most of the failures that are found in normal use fall into this group, and these are very small in number. Mechanical failures can be further divided into two groups, excessive force failures and fatigue failures. An excessive force failure is defined as a failure due to the application of a destructive force greater than that which a new, average, good connection can withstand. The probability of such a failure for good connections is directly related to the care with which the connections are handled and is generally very low.

A fatigue failure is defined as any mechanical failure in which the reduction in fatigue life was the primary cause of failure. If a connection is repeatedly stressed to a value below its breaking point, by definition it is being fatigued, and its time of ultimate failure will have been significantly influenced by its fatigue history. Thus most mechanical connection failures are due to fatigue, and since most connection failures are mechanical, it is apparent that most of the connections which fail in service do so because of fatigue.

The basic measure of quality of a permanent connection is its life. Any adverse environment to which the connection is subjected usually results in a reduction in either its electrical or mechanical life. There is no environment present in a typical central office which will cause a significant reduction in the electrical life of connections of the types and qualities considered in this study so long as the connection remains mechanically secure. Two of the most severe environments in a central office are the small-amplitude vibrations due to equipment operation and the occasional bending of the connection during testing and wiring changes. These are both of a fatigue nature, and if the connection prematurely fails, it will probably be due to fatigue. Other environments such as temperature, corrosion, and humidity will in general not cause connection failure but will reduce the fatigue life, as shown in this study, and thus hasten the failure of connections. It follows, therefore, that most connection failures in service will be fatigue failures and that the basic measure of mechanical quality of a permanent connection is its fatigue life.

The results of this test program offer a number of arguments supporting the hypothesis that fatigue life is the most important mechanical characteristic of a good connection. These will be presented in the form of statements and then the supporting data and reasoning will be discussed.

(1) The ultimate mechanical strength of a connection is a poor measure of the fatigue life remaining in the connection.

Test 15 (Fig. 18) illustrates the above statement for percussive welds. In this test, connections were fatigued a predetermined number of cycles by the lightly loaded bending method and then the surviving connections were destructively tested. The results show that, at 100 per cent of the average fatigue life, the average strength of the surviving connections was approximately 95 per cent. In other words, when almost all of the fatigue life of the connection was expended, it showed only a 5 per cent loss in strength. The surviving connections were actually in bad shape, but a destructive strength test would have indicated hardly any degradation.

A second statement, closely associated with the first, is as follows:

(2) Loss in the ultimate mechanical strength of a connection is generally coincident with an even greater loss in its fatigue life.

Test 15 supports this statement. Further support is provided by the inferior weld test, Fig. 19. Inferior percussive welds were manufactured on purpose by using insufficient capacitance in the welding power supply, and the destructive strength and bending fatigue life distributions determined for these inferior welds. The results show that the destructive strength average dropped to 55 per cent of the good weld value and the bending fatigue average dropped to 17 per cent of the good weld value. Thus the fatigue life is approximately three times as sensitive an indication of inferior welds as destructive strength tests.

3.2 *General*

The most important factor affecting the fatigue life of a permanent connection is the manner in which the wire is brought from the terminal or its configuration. The configuration test, test 14, showed that when the 90° bend in the standard configuration was omitted, the fatigue life of all four types of connections was drastically reduced. The configuration used in test 14 may or may not have been the worst possible fatigue life configuration for the connections, but there can be no doubt that it is possible for the configuration to alter the fatigue life by approximately a factor of two. The results of the configuration test lead to the conclusion that the 90° bend in the standard configuration apparently partially isolates the connection from external wire movements and therefore improves the fatigue life of connections.

In general, the results of the shock tests indicate that all of the connections suffered some mechanical degradation from this environment.

The laboratory shock test (fatigue life) and both railroad shock tests show that in general it is the high fatigue life connections, i.e., those on the high end of the distribution, which are most affected by the shock environment.

Laboratory shock tests 3 and 4 afford one of the few opportunities for a direct comparison of the fatigue life and destructive strength test methods of measuring the degradation of the connections. The connections of both tests were exposed to the same shock environment and the degradation due to this environment was measured in two ways, (1) vibration fatigue life (Fig. 7) and (2) a destructive test (Fig. 8). Table V summarizes the results of these two tests and presents the degradation as a percentage of the control value.

Inspection of Table V indicates that for all four types of connections fatigue life is the more sensitive indicator for the measurement of shock degradation. This table thus further substantiates the statement that the

TABLE V — SHOCK DEGRADATION AS MEASURED BY FATIGUE LIFE AND DESTRUCTIVE TESTS (PERCENTAGE DEGRADATION DUE TO SHOCK)

Connection Type	Fatigue Life	Destructive Test
Soldered	23%	15%
Solderless wrap	24%	10%
Percussive weld	23%	1%
Resistance weld	22%	8%

mechanical strength of a connection is a poor measure of the fatigue life remaining in the connection.

The results of the central office and outside plant temperature tests, 7 and 8 respectively, showed, in general, a small but significant loss in fatigue life for all types of connections except for percussive welded connections. The degradation experienced by percussive welded connections from both temperature tests was greater than that of the other three types and amounted to approximately 30 per cent of the control fatigue life. Even this significant loss, however, did not prevent percussive welded connections from placing second in the order of merit.

3.2.1 *Composite Vibration Fatigue Life*

The vibration fatigue life data from all of the tests without insulation have been added together to form a composite or summary for each type connection. This summary is presented in Fig. 20 and Table VI; the table contains a list of the tests and the number of connections of each type which were included. The order of merit based on the vibration fatigue life for the connections without insulation is as follows:

1. percussive weld
2. soldered
3. solderless wrap
4. resistance weld.

A similar summary for the connections with insulation is presented in Fig. 21 and Table VII. It should be noted that the data scatter, as indicated by the length of the bar in the soldered and solderless wrap distributions, has increased, compared to the distribution without insulation, whereas the scatter of percussive and resistance welded data

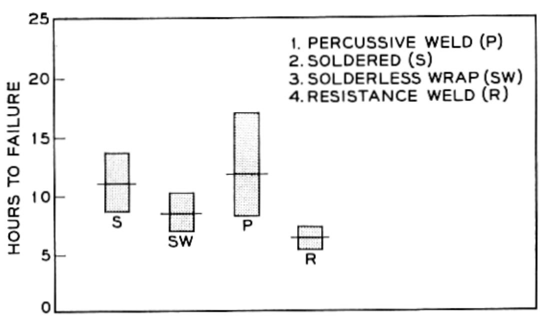

Fig. 20 — General wiring vibration fatigue life summary (without insulation); order of merit, based on vibration fatigue life.

TABLE VI — VIBRATION TEST DATA SUMMARY (WITHOUT INSULATION)

Test Description	Test Number	Number of Data Points From Each Test			
		Soldered	Solderless Wrap	Percussive Weld	Resistance Weld
Vibration	1	40	40	37	40
Temperature					
central office	7	20	20	20	20
outside plant	8	20	20	20	20
Corrosion					
3 months	9	10	10	10	10
6 months	10	10	10	10	10
Humidity	11	20	20	20	20
Totals		120	120	117	120

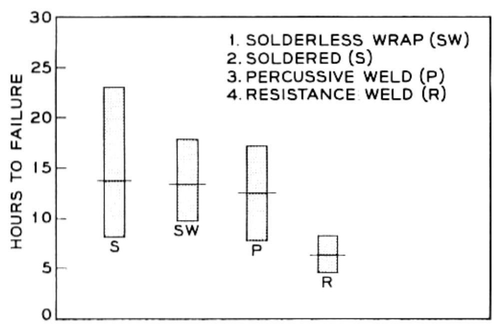

Fig. 21 — General wiring fatigue life summary (with insulation); order of merit, based on vibration fatigue life.

TABLE VII — VIBRATION TEST DATA SUMMARY (WITH INSULATION)

Test Description	Test Number	Number of Data Points From Each Test			
		Soldered	Solderless Wrap	Percussive Weld	Resistance Weld
Vibration	2	20	20	20	20
Configuration	14	20	20	20	20
Shock					
Laboratory	3	14	20	18	20
Railroad					
Noncushioned	5	10	10	10	10
Cushioned	6	10	10	10	10
Totals		74	80	78	80

has remained about the same. This is probably due to the insulation effect on the soldered and solderless wrapped connections. These connections were manufactured with the insulation in close proximity to the terminal, which is the normal wiring procedure; however, the exact location of the insulation was not accurately controlled and this resulted in a somewhat random insulation effect.

The order of merit based on the vibration fatigue life of the connections with the insulation is as follows:

1. solderless wrap
2. soldered
3. percussive weld
4. resistance weld.

It is the opinion of the author that the "without insulation" data is more important than the "with insulation" data, because the presence of insulation close to the connection cannot be depended upon in the case of soldered and solderless wrap connections. The worst case, without insulation, is therefore the most important. Inspection of the bar graphs in Fig. 20 and 21 shows that there is very little difference in the low end of the soldered and solderless wrap distributions, which indicates that the low fatigue life connections in the "with insulation" distribution were essentially without insulation. Since it is the low fatigue life connections which are most vulnerable to early failure, it follows that the most meaningful comparison should be based on the "without insulation" data.

If the presence of insulation could be assured, as in the case of the modified solderless wrap which has one turn of insulated wire as part of the connection, the fatigue life would undoubtedly be consistently higher and the "with insulation" data would be more meaningful.

The above two summaries were obtained by adding the fatigue life data of the tests involved to form a composite distribution. This procedure weights the final distribution according to the number of connections in each type of test, and this is certainly not the only way to treat the data. However, all four types of connections were treated equally, and so a comparison between them is meaningful.

3.2.2 *Orders of Merit*

An order of merit based on vibrational fatigue life statistical distributions was obtained from all environmental tests which compared the four types of connections and which used vibrational fatigue as a measure of degradation. It is also possible to obtain an order of merit for these tests from the number of stub connections of each type which survived the complete vibrational fatigue life determination. When one connection of a pair failed during the vibration test, the loop was clipped off, leaving the remaining good connection with a wire stub long enough to be destructively tested. Then the vibration test was continued until all pairs of connections had at least one failure. This additional vibration caused some of the stubs from the surviving connections to fail. Since all four types of connections initially had the same number of test connections, an order of merit can be obtained from the number of surviving stub connections by assigning the first position to the connection type which had the highest number of surviving stubs, second place to the type having the next highest number, and so forth. This procedure has meaning because all stub connections remained on the vibration machine until the end of the vibration period. Table VIII compares the orders of merit obtained from the number of stubs remaining with those obtained by consideration of the fatigue life distribution of the four types of connections.

In combining the orders of merit in Table VIII, it seems reasonable to assume that the soldered and percussive welded connections are of approximately equal merit and should share the number 1 position in an over-all vibrational order of merit as follows:

1. {soldered / percussive weld}
3. solderless wrap
4. resistance weld.

It seems desirable to establish an over-all order of merit, shown in Table IX, for the four types of connection considered in the general wiring portion of this study. It is possible to do this because approximately equal numbers of all four types of connections were subjected to the various environments at the same time and under identical conditions. It should be remembered, however, that the best connection in the

TABLE VIII — ORDER OF MERIT COMPARISON

	Order of Merit							
	Based on Number of Surviving Stubs				Based on Fatigue Life			
	First	Second	Third	Fourth	First	Second	Third	Fourth
Percussive weld (P)	6	2	3	0	2	6	3	0
Soldered (S)	4	6	1	0	8	2	1	0
Solderless wrap (SW)	1	3	7	0	1	3	7	0
Resistance weld (R)	0	0	0	11	0	0	0	11

Numbers represent the number of firsts, seconds, thirds, and fourths for each rating method.

TABLE IX — OVER-ALL ORDER OF MERIT

Description	Number of Connections	Order of Merit			
		First	Second	Third	Fourth
Vibrational fatigue	1600	S&P	—	SW	R
Lightly loaded bending fatigue	160	P	SW	S	R
Heavily loaded bending fatigue	152	SW	P	S	R
Over-all order of merit based on fatigue	1912*	P	S	SW	R

Legend: S, soldered; SW, solderless wrap; P, percussive welded; R, resistance welded.
* Sum of above three groups of connections.

over-all order of merit was not necessarily the best under every environmental test, but was best only in an average sense.

Percussive welded connections were assigned first place because they shared first place with the soldered in the most important group of tests, vibrational fatigue (1600 test connections), and were also first in the lightly loaded bending tests. Soldered connections were assigned second place on the basis of their sharing first place in the vibrational fatigue tests. Resistance welded connections were assigned last place for obvious reasons, leaving third place for solderless wrapped connections.

It should be remembered that the soldered and solderless wrapped connections used in this study were of the same quality as those in wide-scale use in the telephone plant today. These connections have given and continue to give satisfactory service in the central office environment.

On the other hand, the percussive welded connections used in this study were of higher quality than those which have been used in special applications. This higher quality results from the use of the monitoring technique described in Ref. 1. These monitoring criteria are strongly recommended for all applications of percussive welding to assure the high quality of which the process is capable.

3.2.3 *Summary*

Table X, connection suitability as a function of environment (based on fatigue life), attempts to present the results of the general wiring portion of this study in a manner which would aid in the selection of a connection for a given environment. A rating number, based on the fatigue life of the connections, is assigned to each type of connection for

Table X — Connection Suitability as a Function of Environment (Based on Fatigue Life)

Test Description	Test No.	Fatigue Method*	Without Insulation				With Insulation			
			Soldered	Solderless Wrap	Percussive Weld	Resistance Weld	Soldered	Solderless Wrap	Percussive Weld	Resistance Weld
Vibration test	1&2	VIB	7	5	8	4	10	8	8	4
Shock test laboratory	3	VIB					8	7	6	3
Shock test railroad noncushioned	5	VIB					9	7	6	3
Shock test railroad cushioned	6	VIB					9	7	7	3
Temperature test central office conditions	7	VIB	6	4	6	3				
Temperature test outside plant conditions	8	VIB	7	5	6	3				
Three months corrosion	11	VIB	7	5	8	4				
Six months corrosion	12	VIB	7	5	8	4				
Humidity tests	13	VIB	7	5	7	3				
Configuration test	14	VIB					4	6	4	2
Composite	—	VIB	7	5	8	4	7	7	6	3
Lightly loaded bending test	12	LLB					3	5	10	2
Heavily loaded bending test	13	HLB					8	10	8	5

* Fatigue method: VIB — vibration; LLB — lightly loaded bending; HLB — heavily loaded bending.

each test conducted. The table is divided into three general areas defined by the double lines. The top area is concerned with the vibration fatigue life both with and without insulation, the middle area is concerned with the lightly loaded bending fatigue method, and the last area at the bottom is concerned with the heavily loaded bending fatigue method. The rating numbers within any of the three areas are consistent among themselves. However, comparison of rating numbers from different areas has no meaning.

The rating system used is as follows: the number 10 was assigned to the highest value of fatigue life in a given area. The other rating numbers in the same area were generally assigned according to the percentage of fatigue life they had, compared to the highest value. Some adjustment of the rating numbers has been made to take into consideration the orders of merit. In general, the rating numbers are closely associated with the fatigue life of the connections involved and offer a reasonably good index as to how well a connection will perform in a given environment.

Table X should be particularly valuable in selecting a connection for a given environment. The value of Table X is derived from the fact that, within a given fatigue area, valid cross comparisons can be made. Thus it is possible to get an idea of the degradation caused by shock on a percussive welded connection as compared to that caused by temperature or humidity or some other environment totally different from shock on, say, a soldered or solderless wrapped connection. These cross comparisons are possible because the common parameter chosen to measure degradation was fatigue life.

The "composite" listed under test description in the vibration fatigue area of Table X was obtained from the results of the vibration fatigue life summaries of Section 3.2.1.

The effect of insulation on the wire in the vicinity of a connection is apparent from the vibration portion of Table X. The percussive and resistance welded connections are relatively unaffected by the presence or absence of insulation. This result was expected, since the manufacture of these connections requires the insulation to be removed from the area near the welds. The soldered and solderless wrapped connections show a significant increase in their fatigue life when insulation is close to the connection.

Since improved vibration fatigue life is obtained when a soldered or solderless wrapped connection has insulation close to the terminal, it seems reasonable to inquire about the possibility of manufacturing these connections with the insulation always close to the terminal in order to take advantage of the increased fatigue life. It seems unlikely that this could be done for the soldered connections, because of the adverse effect of the heat on the wire insulation. In the case of the solderless wrapped connection, however, modified wrapping bits are available which place a turn of insulated wire around the terminal. The average vibration fatigue life of these modified wraps would undoubtedly be greater than either the "with" or "without" insulation connections tested in this program. It is the opinion of the author that the modified solderless wrapped connections could show enough improvement in their fatigue life to take over first place in the order of merit as opposed to third place without the modified wrap. In summary, it can be stated that a significant improvement in vibration fatigue life could be obtained on solderless wrapped connections by using a modified wrap.

It should be pointed out, however, that the need for this increased fatigue life in normal Bell System field applications appears unnecessary in view of the fact that billions of solderless wrapped connections are in use in the telephone plant today and have given excellent service since their introduction ten years ago.

IV. CONCLUSIONS

4.1 *General*

The following three conclusions apply to all four types of electrical connections covered in this study. These connections were made with one size and type of terminal (0.025 by 0.062 inch nickel-silver) and with one type of wire (24-gauge solid copper); consequently, the conclusions may not hold for all types and sizes of terminals and wire.

(1) Assuming adequate electrical stability, a permanent electrical connection can be characterized by its fatigue life. Thus, if the fatigue life of a connection is well defined for various fatigue methods and the effect of adverse environments is determined on these fatigue lives, the mechanical quality of the connection has been established.

(2) A bend in the wire in the vicinity of the connection partially isolates it from external wire movements and significantly improves its fatigue life.

(3) The ultimate mechanical strength of a connection is a poor measure of the fatigue life of a connection.

4.2 *Specific*

(1) Using fatigue life as a basis of comparison and soldered connections as a reference standard, it is concluded that:

(a) monitored percussive welded connections are, in general, superior to soldered connections for the conditions which existed during this study,

(b) over-all, solderless wrapped connections are essentially equivalent to soldered connections, for the conditions which existed during this study, and

(c) resistance welded connections are significantly inferior to soldered connections for the conditions which existed during this study.

These conclusions represent over-all averages for all of the conditions tested. In some specific environments they may be interchanged or reversed. See Table X for details.

(2) Table X gives a good estimate of the comparative fatigue life which can be expected from the four types of connections under the various environmental test conditions.

(3) All four types of connections show loss in fatigue life and destructive strength due to repeated high level shocks.

(4) The shock and vibration experienced by all four types of connections when shipped by railroad express can result in loss of fatigue life.

(5) In general, all four types of connections show some loss in fatigue life due to the temperature tests environment. Percussive welded connections show the most significant loss.

(6) A significant improvement in the fatigue life of solderless wrapped connections can be expected through use of a modified wrap which places one turn of insulation around the terminal.

V. ACKNOWLEDGMENTS

The author gratefully acknowledges the general guidance and encouragement given by C. B. Brown and H. M. Knapp. Thanks are also due to J. C. Coyne for many valuable discussions and to J. J. Dunbar for assistance in the laboratory.

APPENDIX

Connection Manufacture and Quality Control

This appendix describes the destructive strength testing methods used for each type of connection. It also presents the data resulting from these tests in the form of statistical distributions.

A.1 *General Wiring*

All of the connections were made using one type of terminal and wire from two spools.

The terminal was of the solderless wrapped type shown in Fig. 22. It

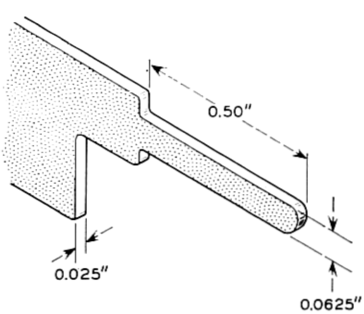

Fig. 22 — General wiring terminal; material is nickel-silver.

was made of nickel silver 0.025 inch thick and $\frac{1}{16}$ inch wide in the area of the connection. The soldered and solderless wrapped connections were made to this terminal in the conventional manner and the percussive and resistance welded connections were made on the $\frac{1}{16}$ inch wide side.

The wire used in all general wiring connections was standard switchboard wire, 24-gauge, solid, tinned copper wire with polyvinyl chloride insulation. Toward the end of the test sequence, the first spool of wire was exhausted and it was necessary to use another spool. The elongations of the two wires, measured over a 10-inch length, were as follows:

1. first spool — 16 to 19 per cent elongation
2. second spool — 15 to 18 per cent elongation.

A.1.1 *Soldered*

The soldered connections were manufactured in accordance with the present standards. They were actually of the wrapped and soldered type, since more uniformity could be obtained by wrapping three to three and one-half turns on the terminal with a wrapping tool and then soldering.

In the case of the soldered connections, there was no generally accepted method for determining the strength of a connection, so a testing procedure was devised. The testing procedure consisted of mounting the test terminal in a universal joint type of arrangement as shown in Fig. 23 and measuring the peak force required to pull the wire completely off the terminal.

This procedure for determining the strength of soldered connections was evaluated by using it to measure the strength of the extreme conditions of soldered connections: (1) a good connection and (2) an extremely poor soldered connection made by wrapping 3 to $3\frac{1}{2}$ turns around the terminal and applying no solder to the connection. Twenty-five connections of each type were tested, and the results are shown in Table XI.

A total of 1040 soldered connections was manufactured for this test program under conditions which assured high quality and uniformity. Half of these were used in determining their vulnerability to various environmental conditions, as described in the main body of the report,

TABLE XI — STRENGTH OF SOLDERED CONNECTIONS

Type Connection	Force Reading in Pounds		
	Maximum	Minimum	Mean
Good connection	7.5	4.8	5.76
Poor connection	3.5	2.6	3.04

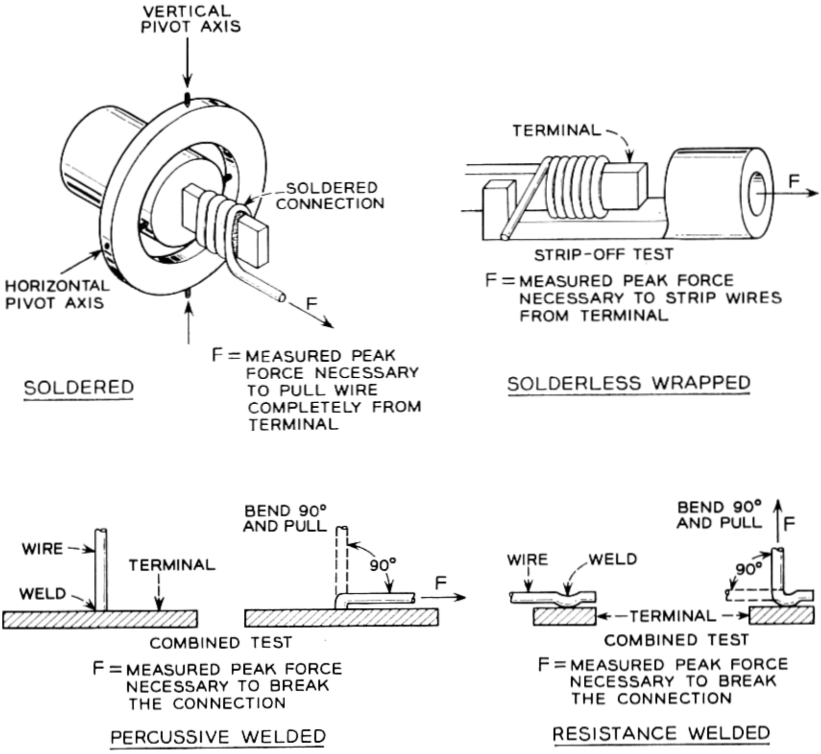

Fig. 23 — Destructive tests.

and the other half were destructively tested according to the procedure outlined above. The results of these destructive tests are presented in Fig. 24.

A.1.2 *Solderless Wrap*

The solderless wrapped connections were manufactured according to present standards, using qualified wrapping bits and wire of the proper elongation. The operator and wrapping bit effect on connection quality was minimized by having half the connections made by each of two operators, who in turn made half of their connections with one qualified bit and half with another. A total of 1040 connections was manufactured, half of which were destructively tested immediately after manufacture in order to determine the quality of the remaining connections, which were used in the comparison tests. The destructive tests were of two

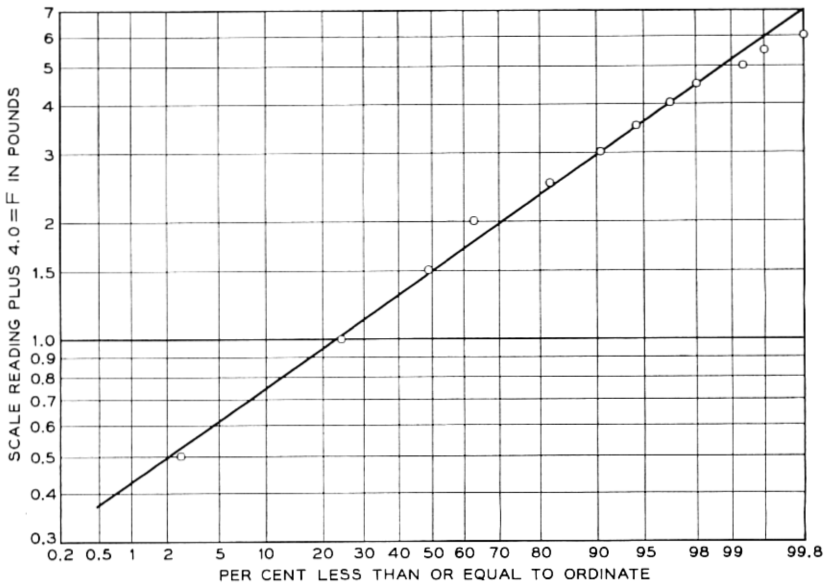

Fig. 24 — Soldered connection destructive strength distribution, general wiring; 590 data points.

types: (1) a standard strip-off test, shown in Fig. 23, which measures the maximum force required to strip the connection from its terminal and (2) a standard unwrap test, which requires that the wire shall be capable of being unwrapped completely from the terminal without breaking.

The distribution of strip-off values for the 260 connections destructively tested in this manner is shown in Fig. 25.

A.1.3 *Percussive Welded*

All of the general wiring percussive welds, with the exception of the inferior weld test, were made using the monitoring criteria developed by J. C. Coyne and reported in Ref. 1. These criteria resulted in welds of high quality, and a quantitative measure of this quality was obtained by destructively testing alternate welds (by order of manufacture). The destructive test used was the combined test, illustrated in Fig. 23, which consists of bending the vertical weld 90° to a horizontal position and determining the peak force necessary to break the connection. A total of 1540 welds (not counting the inferior weld test connections) was manufactured for this test program, and the destructive test data are presented in Fig. 26.

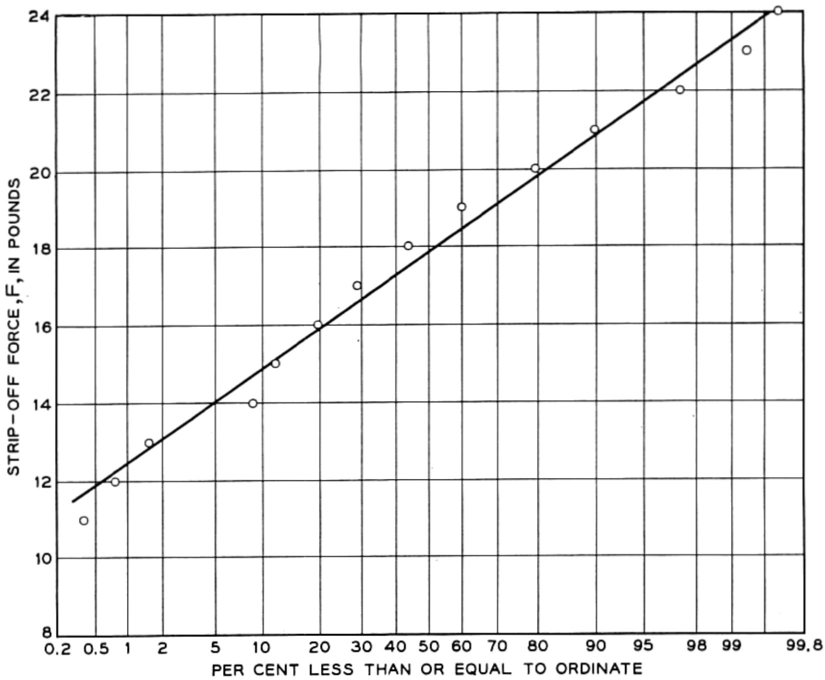

Fig. 25 — Solderless wrapped connection destructive strength distribution, general wiring; 260 data points.

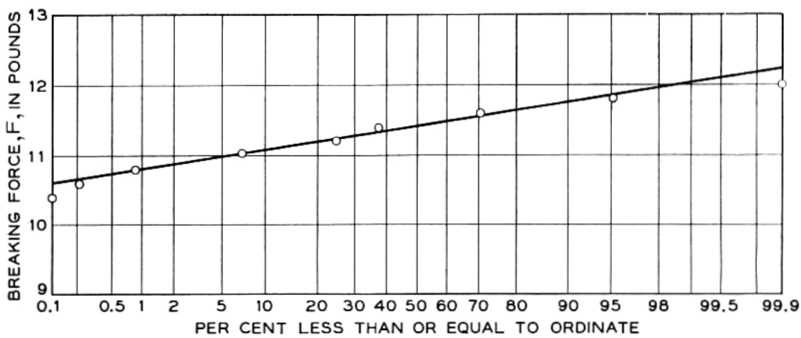

Fig. 26 — Percussive welded connection destructive strength distribution, general wiring; 940 data points.

A.1.4 *Resistance Welded*

Although resistance welding has been used for electrical connections for a number of years, no generally accepted quality requirements or standard method of measuring the weld strength could be found. The resistance welds used in this test program were the best which could be produced after a reasonable amount of experimentation with the process. The destructive strength test chosen was similar to that used for percussive welds — that is, the horizontal wire was bent 90° to a vertical position and the peak force necessary to break the connection was determined. This procedure is illustrated in Fig. 23. Some consideration was given to a test which consisted of pulling the wire horizontally along its original manufactured direction. This type of test yielded very little information about the weld, however, because the connections almost always broke in the wire, well away from the weld area. The destructive test chosen always broke at the weld and thus gave a much better indication of the weld strength.

The weld quality was evaluated by destructively testing alternate connections, by order of manufacture, and thus assuring the quality of the remaining connections for the environmental testing program. A total

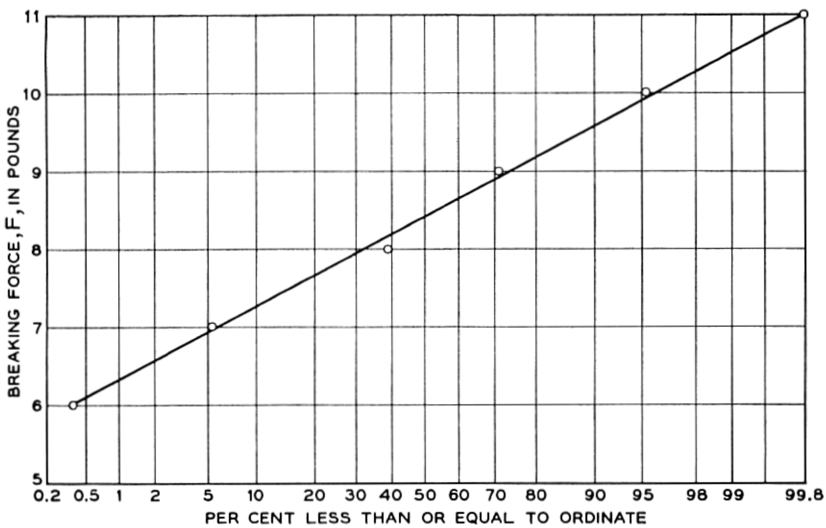

Fig. 27 — Resistance welded connection destructive strength distribution, general wiring; 520 data points.

of 1040 resistance welds was manufactured for this test program, and the destructive test data are presented in Fig. 27.

REFERENCE

Coyne, J. C., Monitoring the Percussive Welding Process for Attaching Wires to Terminals, B.S.T.J., **42,** Jan., 1963, p. 55.