Development of Solderless Wire Connector for Splicing Multipair Cable

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This paper describes the development and laboratory testing of a new high-reliability solderless connector for splicing cable conductors. It includes discussion of the physical parameters which influence the performance of electrical contacts in general. The experimental and analytical techniques which evolved as part of this project permit important reductions in the amount of experimental data required to make reliability and aging predictions, and should be useful in other problems dealing with the appraisal of electrical contacts.

I. INTRODUCTION

The development of new connectors and new techniques for making wire connections has been actively pursued at Bell Telephone Laboratories for some time. Current estimates indicate that well over two billion wire connections are made each year in the Bell System. These connections obviously represent a large investment, and the problems of cost and reliability are becoming increasingly difficult as modern circuits grow in complexity. Performance testing of a connector to establish its reliability is a challenging task.

1.1 *B Wire Connector*

The purpose of this paper is to describe the development and performance appraisal of the B Wire Connector recently released for splicing outside plant multipair cable conductors. As illustrated in Fig. 1, this connector consists of a thin springy liner with sharp tangs on the internal surface, and a brass outer shell encased in a plastic jacket. In use, the conductors to be joined are inserted without removing insulation, and the connector is pressed with a pneumatic tool. The sharp tangs penetrate the insulation and establish contact with the conductors as illustrated in Fig. 2. The individual tangs act as springs, storing en-

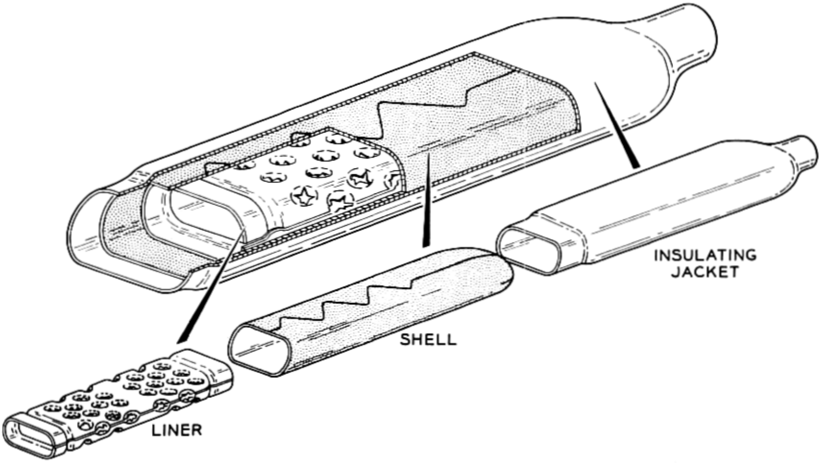

Fig. 1 — B Wire Connector.

ergy to maintain intimate contact with the conductors over the long service life of the device. Electrically, the contact is equivalent to a soldered joint, and therefore is suitable for use in any type circuit where multipair cable may be used. Demand for the B Wire Connector is expected to reach about 250 million per year with resulting annual savings of several million dollars.

1.2 *Reliability and Aging Requirements*

The application for which the B Wire Connector is intended demands the utmost in reliability. The connector, of course, is a series element; a typical cable circuit has a splice every 500 feet or so, often as many as 20 splices in a line. The connections are made under field conditions,

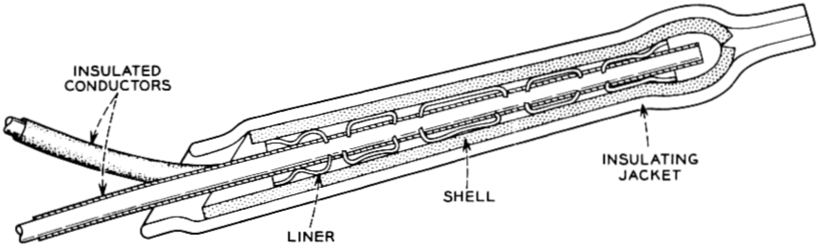

Fig. 2 — B Wire Connector — cross section after pressing on wires.

and are expected to match the service life of the cable, frequently well over 40 years. The splices are enclosed in splice cases or lead sleeves, many of which are hermetically sealed.

When reduced to quantitative values, the reliability requirements are very high indeed. Consider a one-mile run of 2424-pair cable, with ten splices. 48,480 connections are needed, and if 0.1 per cent or 48 of these are bad initially, or become bad in time, 48 or 2 per cent of the circuits would be lost, neglecting the possibility that two bad connections could occur in the same circuit. Similarly, at a failure rate of 0.01 per cent or 1 in 10,000, five circuits would not be available. To assure satisfactory field acceptance, and to allow margin for other sources of failure, target values for the inherent reliability of the connector were established at 1 in 100,000 after 40 years of aging in the outside plant environment.

1.3 *Performance Appraisal Methods*

The appraisal of a device for reliability and performance requirements such as these is always a very difficult and challenging task. As part of this project, a number of advances have been made in the techniques usually used for contact appraisals so as to reduce the amount of experimental data required and to improve the precision of the aging predictions. Some of these techniques are applicable to development work on other types of connectors, and will be discussed in this paper. First it is necessary to describe the mechanisms which influence an electrical contact.

II. CONTACT MECHANISMS

Wire connectors in use in the Bell System today take many forms, ranging from the time-proven binding post, through the solderless wrapped devices, to the newer insulation-piercing, quick-connect terminals. Although radically different in many of their features, these devices have much in common — the basic mechanisms that influence the behavior of the contact are the same. In all of them the circuit is established by clamping together two metallic elements, the wire and the terminal. Circuit continuity is established through the areas of metal-to-metal contact. This contact can be considered to have two components of "contact resistance": (1) constriction resistance due to the convergence of current paths within the parent metal to the relatively small points of contact, and (2) interfacial resistance due to the possible presence of resistive surface films.

A number of variables influence the actual value of the contact resistance in a given connection. Some of these can be controlled quite well through proper selection of materials and platings, geometry, etc. Others tend to be more random in nature: for example, the fine-grain details of surface roughness or oxide coverage which would influence the actual areas in contact at a given loading. Due to the random nature of some of these mechanisms, a distribution of contact resistance may be expected. The spread or range of resistance is a measure of the control or reproducibility of a connector, and thus tends to indicate its reliability. To hold the degree of variability to a minimum, it is necessary to understand the various environmental and aging mechanisms applying to a particular design.

Having established an initial contact of a given quality, one must be alert to possible degradation of the contact with time. This is likely to happen as a result of corrosion, stress relaxation, "breathing" of oxidizing atmosphere due to contraction and expansion of connecting parts consisting of different materials, or mechanical disturbance. A good degree of mechanical rigidity, with adequate contact force and energy storage to maintain these forces over the years, are necessary design features to achieve long service objectives. With inadequate provision for these requirements, high resistance and noisy connections are inevitable, and under dry circuit conditions (low-voltage, low-current signals) barrier films can easily cause complete circuit failure. The requirements for sufficient areas of intimate "gas tight" contact and for energy storage have been well known for some time and were studied in some detail during the development of the solderless wrapped connection.[1]

III. MEASURING TECHNIQUES

Measurement of the resistance distribution and aging trends suggested above poses quite a challenge. For a "good" connector design, i.e., one with low contact resistance, the variation of contact resistance from sample to sample may be in the order of a few microhms. Resistance measuring techniques commonly used in the past for the appraisal of contact devices have been capable of resolving joint resistances only to the low milliohm range. With these techniques it is possible to single out "high-resistance" joints but not to study the statistical distribution of "good" joints. The sample sizes needed to establish reliability rates and to draw conclusions about designs and design variables with these relatively insensitive measuring techniques are prohibitively large. On the other hand, with experimental data of sufficient precision, the behavior of the many variables can be studied in much greater detail, and analytical techniques can be brought to bear so as to reduce drastically the amount of experimental data required. For effective analysis by statistical techniques with reasonable sample sizes, the data must be collected with instrumentation sensitive enough to permit the quantitative measurement of differences in resistance levels from joint to joint. Also, for analysis of the aging mechanisms in types of connectors where this is of concern, changes in contact resistance with time must be measurable at short time intervals (several days or a week). If the above requirements are met, statistical study of contact resistance distributions is possible — both initially and after any desired interval of normal or accelerated aging — and reliability rates can be estimated with small sample sizes.

Techniques for measuring fractions of a microhm of resistance have been known for years. The problem in measuring contact resistance on actual devices to these levels of accuracy lies principally in separating the variables in such a way that the experimental errors do not swamp out the resistance to be measured. A typical device, for example a connector joining two wires, may be thought of as a two-terminal black box, on which only external measurements may be made. The various resistive elements within the box include the internal resistances of the lead wire and connector in addition to the contact resistances between wires and connector. The normal tolerances on the internal resistances, due to uncertainties in wire diameter, length, temperature and resistivity, are generally larger than the true contact resistance of connectors of high enough quality to be of interest for long-term service on dry circuits. These uncertainties must be either eliminated or accurately compensated if the desired measurements are to be obtained.

A very simple circuit has been developed to permit resistance measurements of the kind contemplated here. This circuit, as shown in Fig. 3, is a modified Kelvin bridge in which the unknown resistance of the contact is compared to a "standard," which is an accurately controlled length of one of the lead wires.

The circuit has a number of features which reduce experimental errors:

1. Variations in lead wire diameter and resistivity are compensated exactly by proportionate changes in resistance of the standard.

2. Resistance measurements are insensitive to temperature changes, at least to the extent that the unknown has the same temperature coefficient as the standard.

3. The effects of thermal potentials can be balanced out in dc bridge measurements by using normal and reverse polarity of test current.

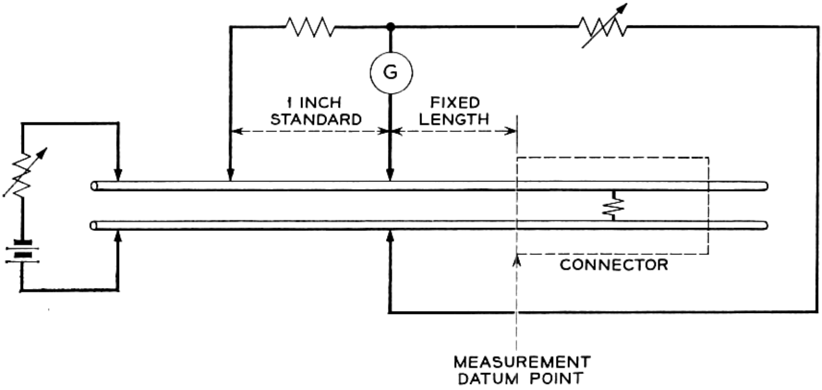

Fig. 3 — Modified Kelvin bridge — setup for loop resistance measurement.

4. The effect of variable resistances due to the connection of the sample to the test set (frequently a source of appreciable error) may be made arbitrarily small by putting them in series with the high impedance arms of the bridge.

The loop resistance measurement, which includes the internal resistance of the lead wires and connector in addition to the contact resistance, Fig. 3, can be used effectively to determine variations in contact resistance between connections, and to measure changes in contact resistance with time. To keep the experimental errors to a minimum, these measurements require very close control of the reference points from which resistance measurements are made. With the measuring equipment used, mechanical tolerances are such that the average variation in loop resistance due to these factors is about ±4 microhms (for 19-gauge conductors and 100 milliamperes test current).

In some cases it is possible to make a more cumbersome measurement than the simple "loop" measurement shown in Fig. 3 so as to separate the various "black box" resistance elements from the contact resistance itself. Modifications in the test set connections as shown in Fig. 4 have been made for this purpose. The unknown bridge arm in Fig. 4(a) includes the resistance of one of the lead wires in to the point of contact and the contact resistance between the two wires. In Fig. 4(b) the unknown contains merely the resistance of the lead wire to the "centroid" of the contacts. The difference between these two readings gives us the contact resistance by itself. These multiple measurements are quite accurate for simple point-contact configurations. For more complicated structures having distributed contacts, the observed resistance must be interpreted in terms of the distribution, somewhat analogous to the

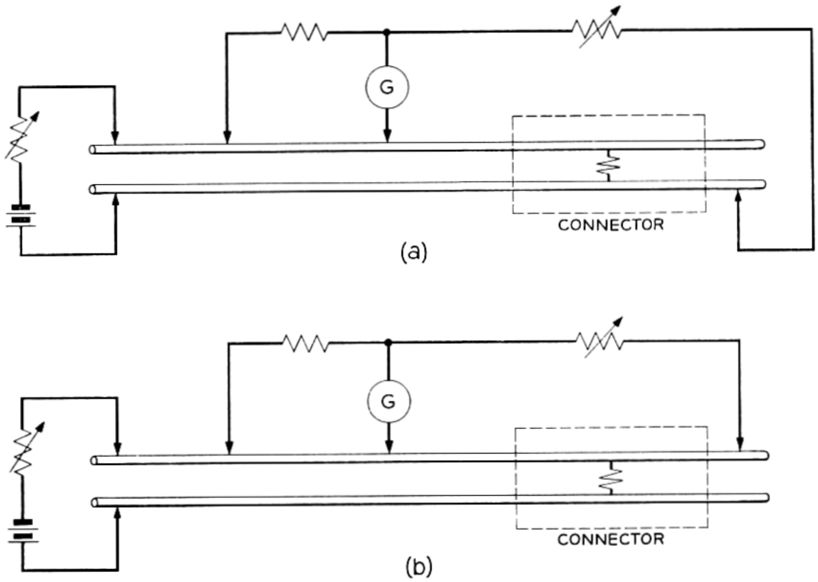

Fig. 4 — Modified Kelvin bridge. Circuit (a) is used to measure the resistance of the top lead wire in to the point of contact, plus the resistance between the two wires. Circuit (b) measures merely the lead wire resistance. The contact resistance is calculated from these two measurements.

input observations on the distributed parameters of a transmission line. In many cases the primary interest is in changes that occur with time rather than in the absolute value of contact resistance, and the more straightforward loop resistance measurement is sufficient for these purposes.

IV. AUTOMATED MEASURING APPARATUS

The need for automated measurements and streamlined data handling was recognized in the early development stages of the B Wire Connector. The manual bridge described in Section III was automated to read and record joint resistances of groups of up to twenty joints automatically. This equipment is shown in Fig. 5. A block diagram of the automated bridge giving major components is shown in Fig. 6. The basic circuit is the same as for the manual bridge. The self-balancing feature is obtained by using the bridge unbalance voltage as the input to the servo-system of a self-balancing potentiometer. The shaft position of the potentiometer, directly related to the resistance measured, is encoded and converted into digital form for direct recording on punched cards or for

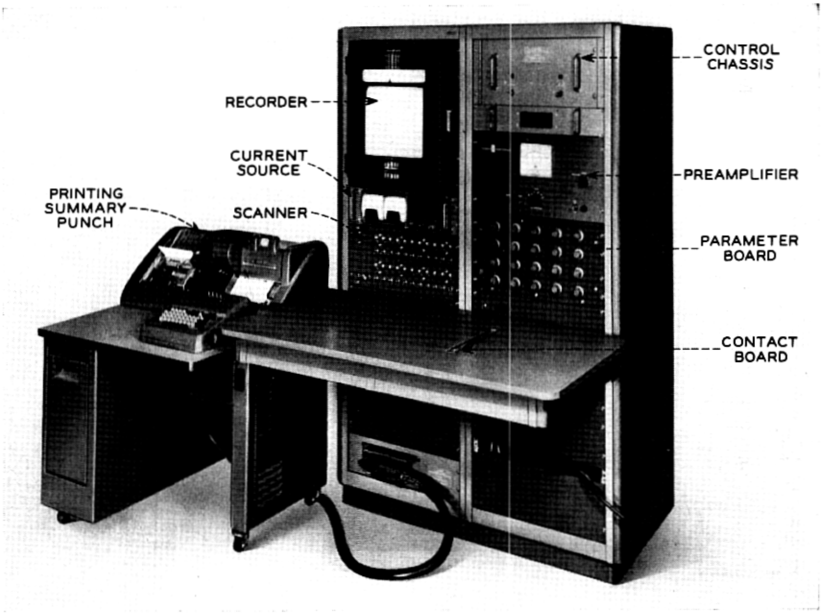

Fig. 5 — Automated, self-balancing bridge for repetitive joint resistance measurements.

visual readout. A timing unit controls the readout, current reversal and the scanner switch by which connections to individual joints mounted on a board are made.

Fig. 7 shows a mounting board with 16 joints. The board also includes four looped conductors, which are used as controls to detect possible errors due to misalignment or shifting of the mounting board relative to knife-edge contacts on the contact board. The use of controls is arbitrary, of course. In this instance, it will be noted that the length of the loop was random. This mounting arrangement provides good control of reference points and saves considerable time on repetitive measurements.

As noted in Fig. 3, the loop resistance of the joint is compared to the resistance of a "standard" length of wire, in this case, one inch. It has proven convenient to read out the resistance in thousandths of an inch of conductor, measured from the entrance end of the connector, rather than in ohms. For the purpose of this paper, the resistance values plotted have been converted to milliohms. It should be noted that the wire resistance varies with the wire gauge used, and this must be taken into account in comparing one plot with another. The precision or repeatability of the system is well within ten microhms, the actual value

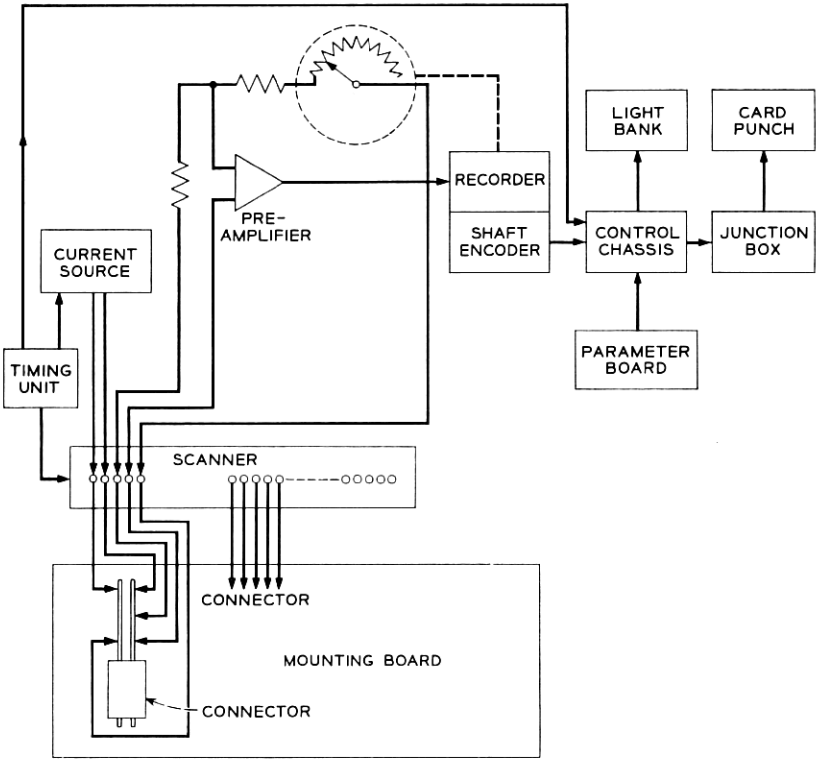

Fig. 6 — Block diagram of automated bridge.

depending on the gauge of the wire being tested and the test current used.

V. EVALUATION OF B WIRE CONNECTOR

The objectives in the design of the new connector were to improve the electrical performance and reliability of the previous standard "pigtail" cable splice, and to achieve economies through time savings by simplifying the splicing methods. The program which led to the final design of the B Wire Connector shown in Fig. 1 will be described in this section.

5.1 *Evolution of Basic Design*

After considering a number of wire joining methods, it appeared that a device which could be pressed onto the ends of unskinned conductors

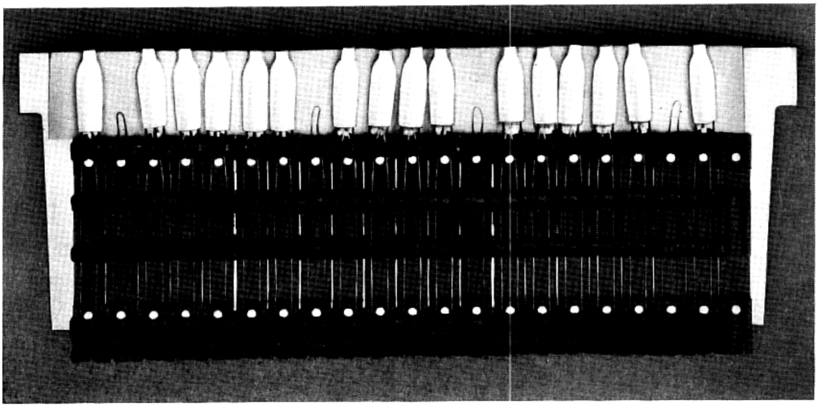

Fig. 7 — B Wire Connectors on mounting board used in automated bridge.

offered the most attractive solution. For this particular application, initial studies showed that such a device should consist of two metallic members: an inner member of relatively hard material with some form of penetrators to pierce the insulation, and a soft, ductile outer member to hold the penetrators in contact with the metallic conductors after the pressing force is removed, and thus minimize the effects of springback. With this principle in mind, two alternative designs were proposed. These two designs used the same soft outer brass sleeve, but differed in the design of the inner member. The liner in connector X consisted of a helix formed from hard drawn rectangular brass wire that had been twisted on its own axis. Connector Y had a liner of thin spring bronze pierced with numerous holes so as to form a multiplicity of tang-like penetrators on the inner surface. At this early stage of the design effort, a number of questions arose, the principal one being, "Which design approach offers the most promise?"

To appraise the performance of connectors X and Y, loop resistance measurements were obtained on small groups of comparably made joints of both types. Measurements were repeated periodically, during which time the connections aged naturally at laboratory ambient. Minute differences in joint resistance resulting from statistical variations in contact characteristics and the aging phenomena were readily discernible with these measurements. Mean connector resistances and standard deviations were plotted vs log time and are shown in Fig. 8.

A study of the aging characteristics, as illustrated by the mean resistance vs time, shows a significant difference between the two connectors: connector Y has a lower aging rate. The plot also gives some

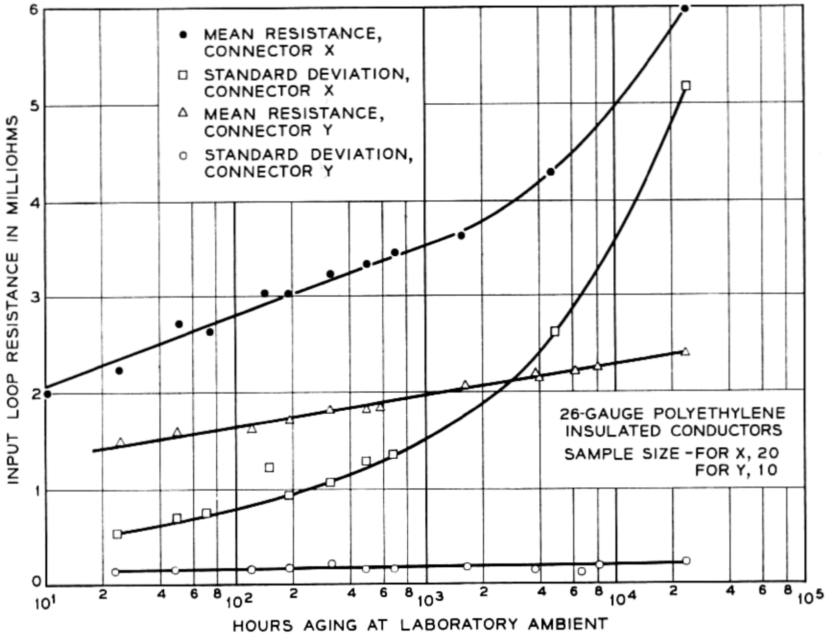

Fig. 8 — Comparative resistance plots for X and Y connectors showing performance under natural aging conditions.

insight as to the fundamental mechanisms affecting the performance of connector Y. The linear relationship of resistance and log time indicates the aging phenomenon is following some exponential law. Further analyses of these and other data suggest that the principal component of aging results from stress relaxation of the soft copper conductor at the various points of contact. Stress relaxation has been studied extensively, is predictable, and can be compensated by the provision of increased energy storage in the connector.

The standard deviation plots are also of interest since they provide an indication of the reliability that may be expected from larger samples. Any significant increase in the deviation with aging is an indication of instability and poor reliability. In view of these considerations, it can be concluded from Fig. 8 that connector Y has both a potentially longer service life and a higher reliability rate than connector X. Fortunately, connector Y is also more manufacturable.

It is of interest to note that the initial performance of the two connector designs is not radically different. Based on the initial results, either design might be expected to give good results. In less than one month of natural aging, however, significant differences in the aging rates of the two designs became apparent, in spite of the fact that only a handful of samples were under study. As verified by subsequent data, a valid choice could have been made between the connectors at this time. It is apparent that the ability of the test method to resolve and detect small changes in resistance is of considerable assistance in predicting the long-time performance of connector designs with a minimum number of test samples.

If the resolving power of the test method were degraded to ±1 milliohms, as an example, a significant difference between the two designs could be detected eventually, after the lapse of a much longer aging time. Also, it is possible to improve the accuracy of the predictions of the standard deviation, in spite of the poor accuracy of the test method, by testing many more samples, and by applying the appropriate statistical principles. Neither alternative offers an attractive substitute for good resolving power in the test method.

Still another alternative, in case the resolving power of the test method is poor, is to resort to accelerated aging. A good example of an accelerated test was used in developing the solderless wrapped connector.[2] Here, the connections were exposed to 105°C for 150 days, with intermittent mechanical disturbance. One criterion for judging the performance of the connector is the magnitude of resistance instability resulting from the mechanical disturbance. The measurements are repeated periodically as the stress relaxation proceeds. Due to the mechanical stability and rigidity of connectors X and Y, mechanical disturbance does not produce significant resistance fluctuations, certainly not any that could be detected by measurements of 1.0- or even 0.5-milliohm sensitivity.

5.2 *Development of Final Design*

To complete the design of connector Y, now known as the B Wire Connector, a number of experiments were conducted in which the pertinent design parameters were varied to determine their effects on the performance. An interesting example is a Latin Square experiment performed to study the geometric variables involved in the design of the perforated liner. In this experiment, three levels of pierced hole size and spacing were studied for each of three different material thicknesses. The results of this experiment are shown in Table I, which is a tabulation of the resistance change after 1400 hours of aging at laboratory ambient for each of the design combinations. An analysis of variance indicates that the 0.005 inch thickness is inferior from the standpoint of contact resistance to either the 0.006- or 0.007-inch thickness at the

TABLE I — LATIN SQUARE EXPERIMENT: RESISTANCE CHANGES DUE TO AGING FOR VARIOUS LINER THICKNESSES AND PIERCED HOLE SIZES
(26-Gauge Pulp-Insulated Conductors)

Hole Size in Inches:	Liner Thickness in Inches			Row Sum:
	0.005	0.006	0.007	
0.025	0.093*	0.001	0.012	
	0.047	0.004	0.001	
	0.026	−0.005	0.001	
	0.020	0.019	0.000	
	0.186	0.019	0.014	0.219
0.030	0.045	0.024	0.009	
	0.024	0.019	0.018	
	0.076	0.019	0.010	
	0.080	0.002	0.003	
	0.225	0.064	0.040	0.329
0.035	0.042	0.003	0.007	
	0.025	0.012	0.005	
	0.019	0.009	0.007	
	0.034	−0.001	−0.002	
	0.120	0.023	0.017	0.160
Column Sum:	0.531	0.106	0.071	0.708

* Resistance increase in equivalent inches of 26-gauge conductor after 1400 hours of aging. This conductor has a nominal resistance of 3.48 microhms/mil.

1 per cent level of significance. The analysis further indicates that the variations occurring between pierced hole sizes are probably due to chance causes. Although differences in performance could be noted with the measuring precision available, this experiment, and others of a similar nature designed to study other variables such as material hardness, tang shape, etc., showed quite clearly that the connector performance was not critically dependent on the minor details of the liner fabrication, and that reasonable manufacturing tolerances were not likely to upset the reliability estimates.

In other experiments, accelerated aging tests were used to good advantage to magnify the effects being studied. One such experiment was used to demonstrate the advantage of tin plating the liner. In this experiment, a group of connections was subjected to cyclically varying humidity. The pulp insulation used on cable conductors is quite sensitive to changes in humidity. Pulp is trapped under compression in the connector, and humidity changes cause an alternate shrinking and swelling of the pulp and consequently a mechanical working of the joint. This test has proven very effective in evaluating the stability of the various contacts within the connector. Fig. 9 shows graphically the behavior of two small groups of joints under this accelerated test. One group has liners with tin plating; the other group has liners without plating.

Analysis of these results led to a good understanding of the manner in which the individual contacts are made. Fig. 2 is a cross-sectional view which shows the liner tangs contacting and digging into the conductor. Due to spring-back, immediately after pressing, small voids occur here and there between the tang and conductor. The mechanical working of the joint by humidity changes causes sufficient movement to dislodge the contacts. Tin plating, however, provides a soft, smearable surface which is evidently quite effective in filling these voids and preventing motion. In addition to better stability, the increased contact area due to tin plating reduces the contact resistance quite significantly, and at the same time reduces the statistical deviation among similar joints. Also, previous work[3] has shown that tin-plated surfaces under sufficient contact pressures are subject to solid-state diffusion, which, of course, would improve the electrical contact as a function of time.

5.3 *Accelerated Testing*

The design and interpretation of accelerated tests, although necessary in many cases, are always both difficult and controversial. Under

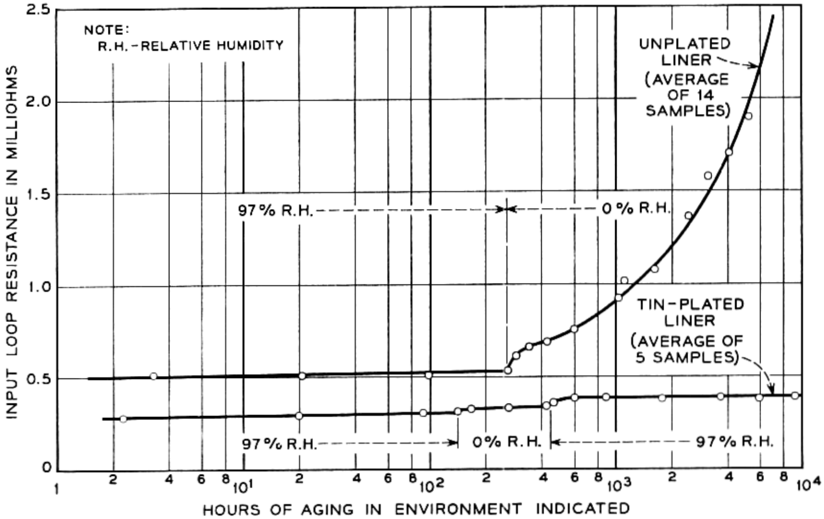

Fig. 9 — Humidity cycling test results which show the superior performance of tin-plated contact surfaces.

all normal environments, a number of aging mechanisms are involved, with various degrees of interaction between them. An accelerated test should ideally accelerate each of the mechanisms equally and preserve the interaction factors; all the pertinent mechanisms must be included or accounted for, and any new mechanisms that may emerge in the future must be anticipated. The development of a test that will satisfy all these requirements is a Utopian goal, and as a practical matter, some degree of engineering risk is inevitable in the use of accelerated tests.

During the development of the B Wire Connector, considerable effort was devoted to the identification of the pertinent aging mechanisms and to the design of accelerated tests to study their influence. One interesting approach has been to design a test that is obviously too severe; if the connector survives this test, then a good factor of safety is assured, and the quantitative calibration of the test becomes unnecessary. The humidity cycling test already mentioned is an example. In its proposed usage on pulp-insulated conductors, the B Wire Connector will always age in a hermetically sealed, low-humidity cable system; and by comparison, the accelerated humidity cycling test is quite severe. The good performance of the tin-plated inserts gives us confidence that the connector has an adequate margin of safety against the effects of changing humidity without further calibration.

In other cases, it has been necessary to attempt a more precise calibration. For instance, we are concerned with the aging mechanism resulting from daily and seasonal temperature fluctuations. These changes cause a mechanical working of the contacts brought about by the differences in coefficient of thermal expansion of the conductor-connector-insulation components. This type of aging could result in contact instability. In addition, the mechanical working of the contact parts may expose the contact areas to the entry of gas and to the formation of oxides or insulating films.

In evaluating the performance of the connector on polyethylene-insulated conductors, the temperature change becomes an especially important variable. The insulation trapped under compression in the connector causes considerable mechanical working of the contacts due to its coefficient of thermal expansion, which is much larger than the coefficients of the metallic parts of the connector. To determine the effect this mechanism has on connector performance, two temperature cycling tests have been devised. These tests have the following temperature ranges: (1) $-320°$ to $+160°$F, and (2) $-40°$ to $+140°$F.

The first test was chosen in order to subject joints to a thermal shock. It consists of heating the joints to $+160°$F and chilling them rapidly by immersion in liquid nitrogen. This test proved effective in causing an increased rate of aging. Fig. 10 shows the accelerated aging curve of polyethylene-insulated 19-gauge copper conductor joints as compared to pulp-insulated conductor joints. Correlation of this and natural aging data helps to estimate the number of cycles representing the expected service life. Relationship between number of temperature cycles of −320° to +160°F and hours of natural aging for pulp- and polyethylene-insulated cable conductors is shown in Fig. 11. These curves indicate that 1 year of natural aging is approximated by something in the order of 50 cycles, and that the equivalent natural aging time increases as the cube of the number of temperature cycles. Assuming this correlation exists for future time, extrapolation of these curves shows that 40 years natural aging is approximated by some 200 cycles.

Since the temperature changes in natural environment are more gradual, the connectors will not be exposed to thermal shocks of the magnitude present in the first temperature cycling test. To represent actual temperature extremes in the field, the −40° to +140°F tempera-

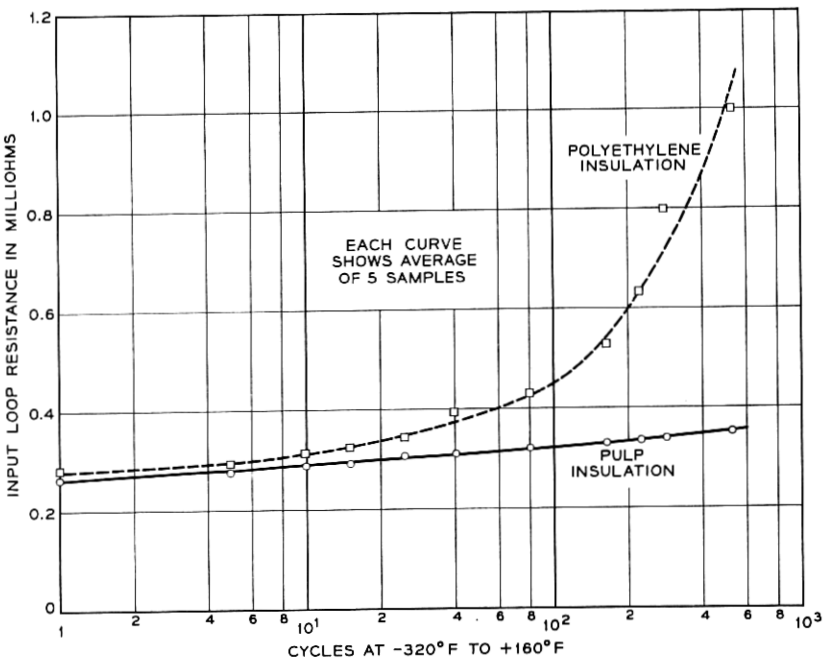

Fig. 10 — Liquid nitrogen temperature cycling test results showing the acceleration of aging for polyethylene-insulated conductors as compared to pulp.

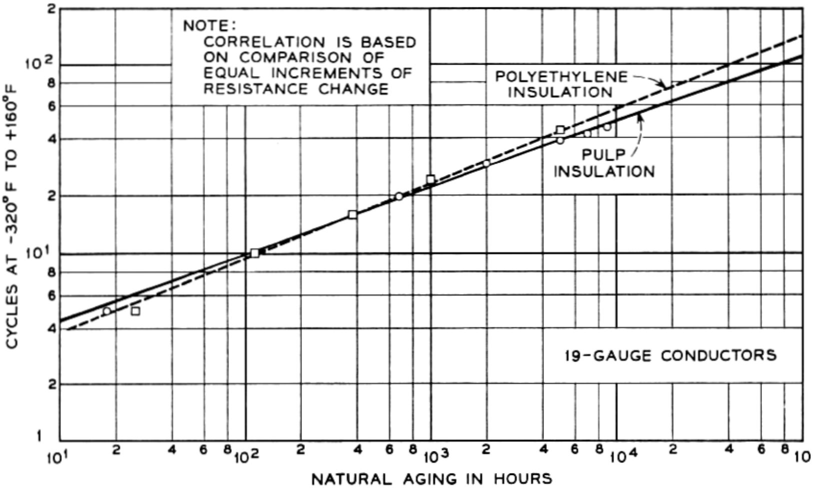

Fig. 11 — Correlation of liquid nitrogen cycles to natural aging.

ture cycle was chosen. The smaller temperature range has the advantage of simulating the natural environment more closely than the thermal shock test and, therefore, is being used exclusively for the final evaluation of plastic-insulated conductor joints. The experimental correlation obtained between natural aging and cycles of temperature cycling between −40°F to +140°F is shown in Fig. 12. Early in the test fewer cycles are required, but the straight-line relationship observed between

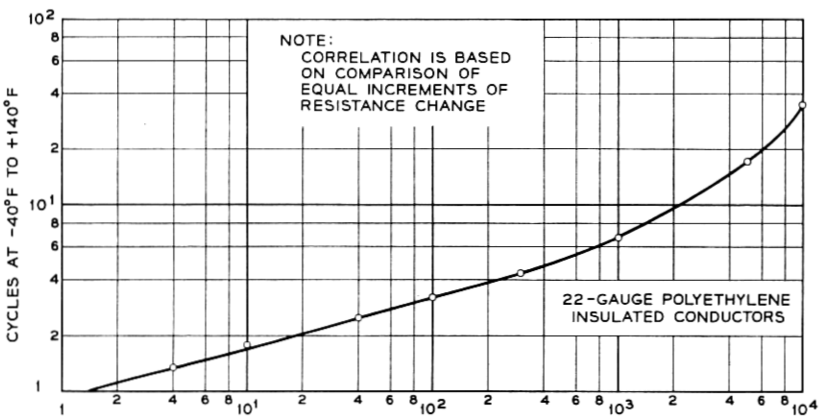

Fig. 12 — Correlation of −40°F to +140°F temperature cycles to natural aging.

liquid nitrogen cycles and natural aging does not hold for the longer −40°F to +140°F temperature cycles. The explanation for this deviation is not known, but it is suggested that presence of nitrogen within the connector may exclude oxygen or other corrosive gases from the critical contact regions of the joint; also, the considerably longer cycle time for the −40°F to +140°F test may have a bearing on this deviation — about 5 cycles per day against 50 cycles for the liquid nitrogen to +160°F test.

An important factor contributing to aging and not included directly in the above tests, is corrosion. Tests where joints are subjected to corrosive atmospheres at constant temperature do not simulate the "breathing" that occurs between contact surfaces due to uneven expansion and contraction of contact members with changing temperature. Calibration of room temperature corrosion tests based on corrosion film thickness may therefore be misleading, because the penetration of the corrosion products between contact surfaces during the short exposure time is likely to be insignificant.

To simulate the "breathing" of corrosive gases between contact surfaces, temperature cycling in the presence of corrosive atmosphere has been tried with reasonable success. This test approaches more nearly a true accelerated aging test because, in addition to forcing a mechanical working of the contacts, it accelerates the corrosion process. Ideally, the same degree of acceleration should be used for the two mechanisms. Attempts to correlate the aging of corrosion-cycled B Wire Connectors and natural aging have not been successful to date. The heavy corrosive films that form in a short period of time interfere with the test-set probes and also significantly change the resistance of the conductor used as a "standard" in the bridge measurement. The test has been useful, however, for comparison testing of different types of connectors.

As indicated above, stress relaxation of the soft copper conductor at the various contact points in the B Wire Connector is a possible aging mechanism. Fundamental experiments have established that relaxation does occur in stressed copper structures and that it is possible to accelerate this process with elevated temperature exposure. For example, previous research has shown that 3 hours at 175°C is equivalent to the stress relaxation during 40 years of natural time.[1] This test when used on the B Wire Connector indicated that the connector contacts were not affected. Although encouraging, we do not consider that this test necessarily approximates 40 years relaxation in the connector, since the elevated temperature may well have changed the true force pattern significantly. For instance, in polyethylene-insulated conductor joints the plastic insulation softens and flows within the connector, changing the internal force distribution.

The philosophy used in applying accelerated tests to the B Wire Connector, and attempts to correlate these with natural aging, are based on correlating equal increments of change in resistance rather than on correlation of a known mechanism, such as stress relaxation, to expected service life. The aging mechanisms are complex, but observations of the resistance behavior itself with time is believed to be more meaningful in this case than a fundamental analysis of the contact members themselves. About a year is required to establish with reasonable accuracy the correlation between accelerated and natural aging relationships using equal increments of resistance change as the criterion. This correlation has been made possible by the development of the precise measuring techniques already described. In any of these accelerated tests, however, a certain degree of engineering risk is taken when extrapolation to long periods of time is made.

5.4 *Reliability Appraisal*

As discussed earlier, the reliability and life requirements for a connector to be used in cable splicing are very demanding indeed. Considerable effort has been expended to determine if the final design of the B Wire Connector meets these requirements. Statistical techniques have been used to predict the performance of large numbers of connections based on the performance of a relatively few connectors. The validity of these predictions depends on the accuracy with which one can define the nature of the distribution which describes the population of the connections and on how this distribution changes with time. In studying the resistance data for the B Wire Connector, it appears that the log normal distribution provides a fairly good fit. Analysis of contact resistance data from simple configurations, such as the classical crossed cylinder, supports this conclusion. In this respect, our conclusions are not directly comparable to those reached in the evaluation of the solderless wrapped connections, where a Poisson distribution is assumed.[2] It should be noted that in the present work we are describing the absolute value of the resistances with a log normal distribution, whereas in the work on the solderless wrapped connection, the degree of resistance instability with mechanical disturbance was described with a Poisson distribution.

The reliability of the connector after 40 years of aging in the outside plant environment is of prime importance. As a starting point we have established from resistance measurements on a few hundred connections the initial reliability of the connectors. From the log-probability plot shown in Fig. 13, it would appear that less than one connection in 100,000 would have an input "loop" resistance as great as two milliohms when first made. As discussed previously, the loop measurement, in addition to measuring contact resistance, also includes the resistance of the conductors that are within the connector. Due to the complexity of the contact configuration, it is difficult to determine precisely what portion of the loop resistance is wire resistance. However, from a study of the geometry, the maximum and minimum possible wire resistances within the connector can be calculated, and are 1.73 and 0 milliohms, respectively, for 24-gauge conductor joints. In practice the wire resistance will always be greater than zero, or conversely, the pure contact resistance will always be less than that plotted in Fig. 13. To this extent, the reliability prediction in terms of pure contact resistance would be better than that quoted above.

Although it may be somewhat premature, we believe predictions of the future reliability of these connections can be made with reasonable confidence based on the early test results of the final design. From resistance measurements during a 7000-hour period on a small sample of connections, aging characteristics for the mean loop resistance and standard deviations have been established, as shown in Fig. 14. From the extrapolation of these plots, it is predicted that after 40 years the mean loop resistance and standard deviation will be 0.780 and 0.110

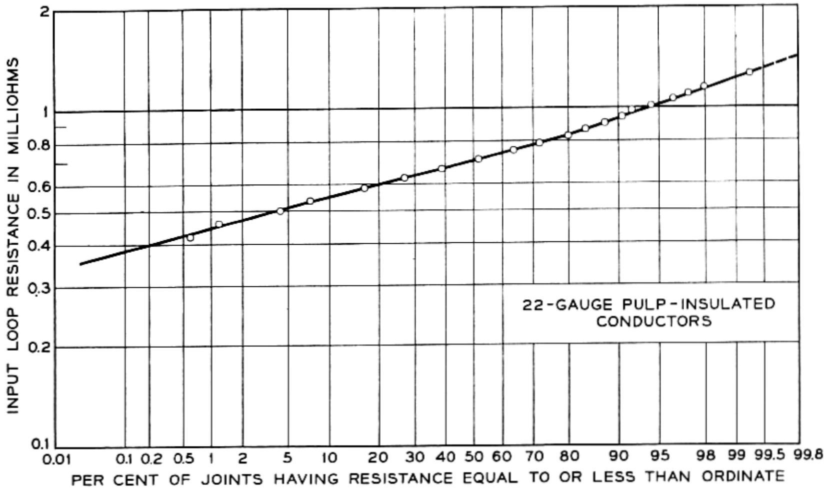

Fig. 13 — Initial resistance distribution of 100 B Wire Connector joints.

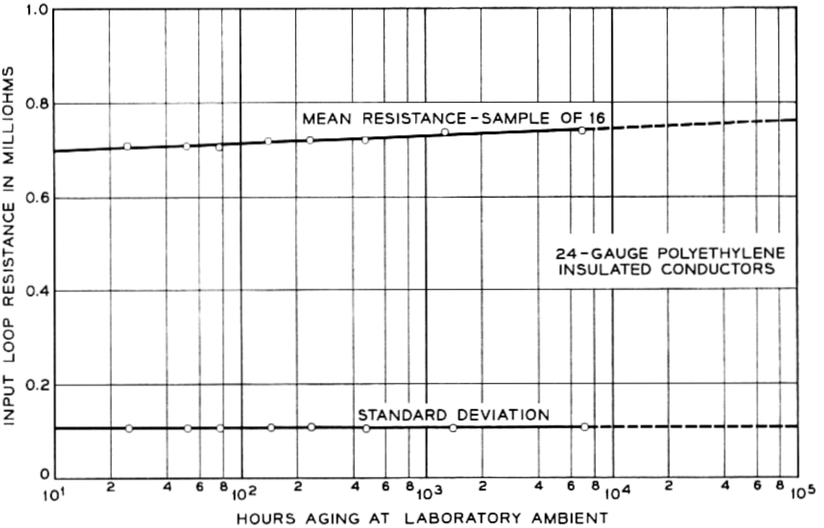

Fig. 14 — Performance of B Wire Connector joints under natural aging.

milliohm, respectively. The distribution of resistance of these connections initially and after 7000 hours of aging at laboratory ambient are shown in Fig. 15. From the predicted values of the mean resistance and standard deviation obtained from Fig. 14, a probability plot showing the distribution after 40 years has been constructed, as shown in Fig. 15.

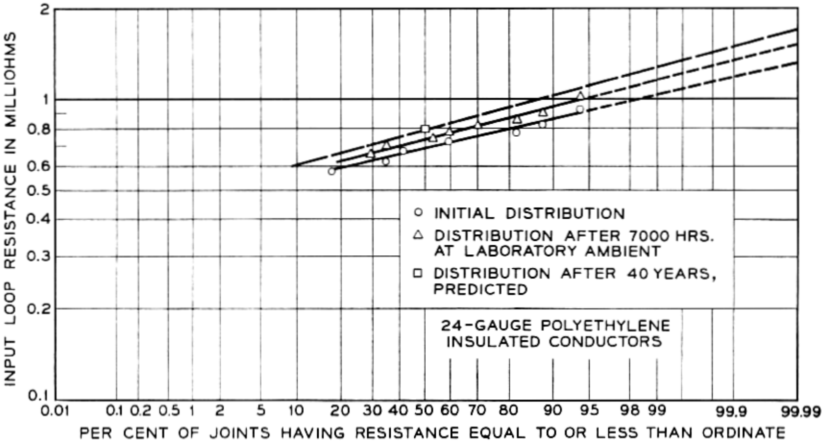

Fig. 15 — Predicted changes in the distribution of B Wire Connector joints with aging.

From the extrapolation of the log-probability plots, it is predicted that about 1 connection in 10,000 can be expected to have a loop resistance as great as 1.3 milliohms initially, and 1.5 and 1.7 milliohms after approximately 1 year and 40 years, respectively.

The tests referred to in this paper are only a few of the many that have been made to optimize the design and study the performance of the B Wire Connector. The other tests include studies made with connectors having only a few penetrators to downgrade the connector performance and make the resistance more sensitive to contact degradation, connectors made with reduced holding forces as a result of thin outer shells, and connectors without tinned liners to accelerate oxidative effects at the critical contact areas. This whole body of test results supports the reliability estimates given here. It is believed that all of the important aging mechanisms have been identified and sufficiently taken into account in the design. The device has been released for field use and so far the inherent reliability is at least as good as expected.

VI. CONCLUSION

The engineering risks involved in appraising a device design for very high reliability and long service life can probably never be reduced to zero. The techniques described here are believed to have minimized these risks in the B Wire Connector, however, and at the same time they have permitted substantial reductions in the laboratory effort required to develop and prove-in this device. Early field experience is considered good confirmation of the basic statistical predictions of initial reliability that were made. Final confirmation of the aging predictions must, of course, await the passage of time.

The experimental techniques described are based largely on the use of laboratory measurements of improved sensitivity which permit the collection of data suitable for more rigorous statistical and experimental analysis than otherwise possible. The data analysis itself has two distinct goals: (1) the study of the fundamental mechanisms which influence the physical behavior of the device, and (2) the formulation of reliability and aging estimates based on a minimum of experimental data through the use of various established statistical and other analytical techniques. In this broad sense, then, the general principles employed in the development of the connector are not new. The degree to which these basic principles have been applied in the past to the design of connectors has been limited, at least in part, by the experimental difficulties in making resistance measurements on actual devices to a sensitivity of much better than ±0.5 milliohm. The measuring circuit and apparatus discussed here are simple and permit an improvement in resolving power or refinement in sensitivity by at least two orders of magnitude. The work on the B Wire Connector clearly shows that important information is lost without this refinement. Many of the specific methods presented here are directly applicable to a broad class of engineering problems having to do with electrical contacts.

VII. ACKNOWLEDGMENTS

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