The Bell System Technical Journal
Vol. 55, No. 5, May–June 1976
Printed in U.S.A.

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

Remreed Contact and Switching Network Evaluation

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(Manuscript received September 17, 1975)

The performance evaluation of the remreed switching network begins with a study of failure modes of the remreed contact and ends with a discussion of results from a field study. Remreed contact-reliability test results show low early failure rates due to high contact resistance and contact sticking. High contact resistance, which characterizes the wear-out mode of failure, is discussed. Remreed switch evaluation results are given. Finally, early field performance of the remreed switching network is assessed in a study using in-service trunk link networks as the source of data.

I. INTRODUCTION

During the development of new switching hardware, many evaluations and tests are performed. The broad objectives of these tasks are to prove and assure that the performance and reliability of the new equipment will meet Bell System needs. High on the priority list of objectives are (*i*) a reliable method of manufacture, (*ii*) an in-service life of 40 years, and (*iii*) maintenance-free performance during operation. This paper summarizes the work conducted at Bell Laboratories on the remreed contact, switch, grid, and frame design to meet these objectives.

To show that the broad objectives could be met by the remreed design, several specific goals had to be achieved. They are:

(*i*) The adequacy of the new hard-gold contact surface had to be established. The ferreed sealed contact, predecessor to the remreed sealed contact, has a diffused gold-silver plated contact surface.

(*ii*) The ruggedness of the sealed contact in the new switch package had to be established to assure that high initial failure rates, induced by handling and shipping, did not occur.

(*iii*) The point where the failure rate of the sealed contact begins to increase, i.e., where the contact begins to wear out, had to be determined. At this point, a mechanism of contact erosion from small arc discharges leads to the high-resistance failure mode. The design goal regarding this failure mode was to produce contact surfaces that exhibited failure rates the same as or lower than the failure rates of the ferreed contact.

(*iv*) The reliability of the control circuits and hardware had to be determined. The remreed network represents the first application of 1A processor technology,[1] including the 946/947 circuit pack connector family and 3-volt collector diffusion isolation (CDI) integrated circuits. Additionally, many of the functions accomplished electromechanically in the ferreed network are replaced in the remreed design with discrete semiconductors (i.e., PNPN transistors and diodes).

(*v*) The establishment of low failure rates for remreed networks in service was needed to verify many assumptions made during the design phase. This was achieved by a field study conducted in various central offices.

Several evaluation methods were used to study remreed equipment. The remreed sealed contacts were "screened" on a computerized data acquisition system. Screening is a term used to describe a testing technique that determines early failure rates of the sealed contact. In general, application of this technique requires very large sample sizes—5000 to 50,000 contacts per test—which are tested for only 1000 operations.

Remreed switch packages and grid assemblies were examined for their ability to withstand levels of shock and vibration normally encountered in shipping via rail and motor freight. In addition to these tests, the switch package underwent exposure to elevated levels of temperature and humidity in an effort to induce early failure. Throughout all of these tests, the operational performance, contact resistance, and sticking behavior of the equipment was measured and/or monitored.

In April 1974, a remreed quality study was initiated. Study offices selected were among those first manufactured. Considerable manufacturing experience had been gained by this time since several hundred trunk link networks (TLNs) containing over 30 million remreed sealed contacts had been shipped to the field. Some of these networks were selected and included in the study. The primary objective of the quality study is to measure the failure and replacement rates of in-service remreed apparatus. The study is fault-oriented, that is, attempts are made to analyze and understand each failure, why it occurred, how it was identified, and how it was corrected.

In an effort to offer a snap-shot view of the usefulness of the evaluations, studies, and surveys, a few results are summarized here. The quality study completed in October 1975 indicates that the remreed sealed contact in this application achieved a very low failure rate. The upper 95-percent confidence interval on the FIT rate is 2.4 while the observed rate is 1.5 FITs. (Here the term FIT is used in its usual sense: 1 FIT is equal to one failure in 10^9 device hours.) The quality study is described in more detail in Section IV.

Another point should be made now regarding the use of a FIT rate. In this paper, the sealed-contact failure rates resulting from laboratory tests are expressed in terms of failures per contact per operation. Then, by estimating the number of times the contact is operated per year, the failure rate is converted to a FIT rate. This is different from the common use of a FIT rate because the failure modes are operation-dependent rather than time-dependent.

The low FIT rates didn't just happen, they are the result of a long, involved, and complex evaluation program that identified several problem areas. When a problem was identified, steps were taken to redesign hardware when it was appropriate and to implement new requirements and tests where necessary.

II. REMREED SEALED CONTACT

The objectives of the sealed-contact evaluation work focused on (*i*) determining early failure rates and failure mechanisms of the hard-gold plated contact surface and (*ii*) determining when wear-out mechanisms caused the sealed contact to become unreliable. Two important failure modes exist for the sealed contact. These are the high contact-resistance mode and the failure-to-release or stuck-contact mode. Both early life and end-of-life performances exhibit these modes.

Reliability theory states that device performance generally fits a "bathtub" curve similar to the one sketched in Fig. 1 (shown on a linear grid). The bathtub curve is a plot of failure rate or hazard against time and has three regions: early or premature failure, useful life or constant hazard, and wear out. The first or initial portion of the curve is the result of early failures which ultimately can be traced to a defective part or an improperly performed step in the manufacturing process. This portion is examined by contact screening tests. The

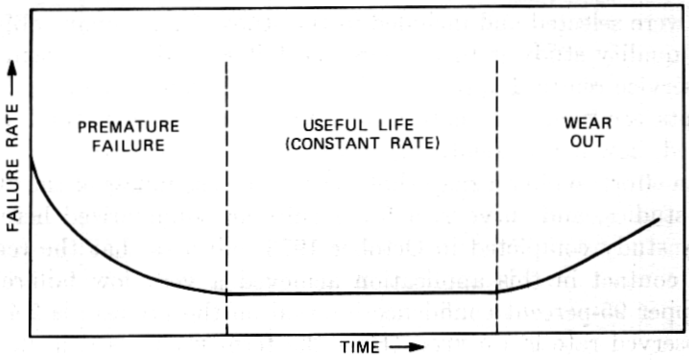

Fig. 1—Typical "bathtub curve."

useful life portion of the curve is a measure of the long-term failure rate and reflects the design reliability of the device in its application. This portion is examined in a field study. If the hazard is truly constant in time, then the reliability can be described mathematically by the exponential distribution and a FIT rate can be determined. The wear-out portion of the curve is, as the name suggests, the time when devices begin to fail as the result of normal use. This part of the curve, examined by life testing, indicates that the stress of use and/or device degradation increases the hazard.

2.1 Data collection

The remreed sealed contact was subjected to many different tests during its development. This section briefly describes one of the tests used to evaluate the 238A sealed contact. The testing facility is a computer-based, data-acquisition system[2] capable of testing 114 sealed contacts at the rate of eight cycles (operate and release) per second. The system does on-line data analyses as it collects the data because of memory-size limitations (both core and disk). During each cycle, the contact is electrically interrogated two times, once to measure its resistance in the operated state and once in the release state to determine whether it failed to release (a stuck contact). Throughout the test, the computer maintains a counter which indicates the number of test cycles completed (number of contact operations completed).

The on-line data analyses are performed quickly enough so that data from succeeding measurements are not lost. The resistance measurements are compared, contact by contact, to eight software-set resistance-threshold values. (These have been chosen to include all possible resistance measurements.) As the test proceeds, counters assigned to each threshold value by contact accumulate data and, when these data are displayed, the result is a histogram for each contact. In addition, three of the eight threshold values have associated tables used to record the current operation number when the contact-resistance measurement first exceeds the assigned threshold value. The contact measurements for failure to release are treated in a similar manner to the resistance data except that there is only one threshold value and its associated first-failure table.

After the test is complete, the resistance histograms and first-failure table data are written from core memory to disk memory and are ready for off-line analyses.

2.2 Early life

In evaluating the remreed sealed contact to determine its early life characteristic, the test data are converted to a hazard statistic using the following formula.[3]

$$z_d(x_i) = \frac{N(x_i) - N(x_i + \Delta x_i)}{N(x_i)\Delta x_i}, \tag{1}$$

where

$z_d(x_i)$ = empirical hazard or failure rate in failures per contact per operation.

x_i = the operation number at the beginning of the ith interval.

$N(x_i)$ = the number of contacts that have not failed by the beginning of the ith interval.

$N(x_i + \Delta x_i)$ = the number of contacts that have not failed by the end of the ith interval.

Δx_i = length of the ith interval in operations.

Using this relationship, $z_d(x_i)$ is calculated for various intervals and plotted at the midpoint of the interval. Figure 2 shows the 238A remreed sealed-contact hazard functions for stick failures and 150-milliohm and 100-ohm resistance failures versus operation number on log-log graph paper. (Two widely separated resistance levels are shown; however, in general, circuit reliability depends on many different levels of resistance. Higher reliability (lower failure rates) accompany greater tolerance to contact-resistance changes.) It is interesting to note that each failure mode produces a straight line with a negative slope. The three hazard curves can be fitted to the equation

$$z(x) = Kx^m, \tag{2}$$

where K and m are constants. This equation, for $m > -1$, is the hazard function for the Weibull distribution with a probability density func-

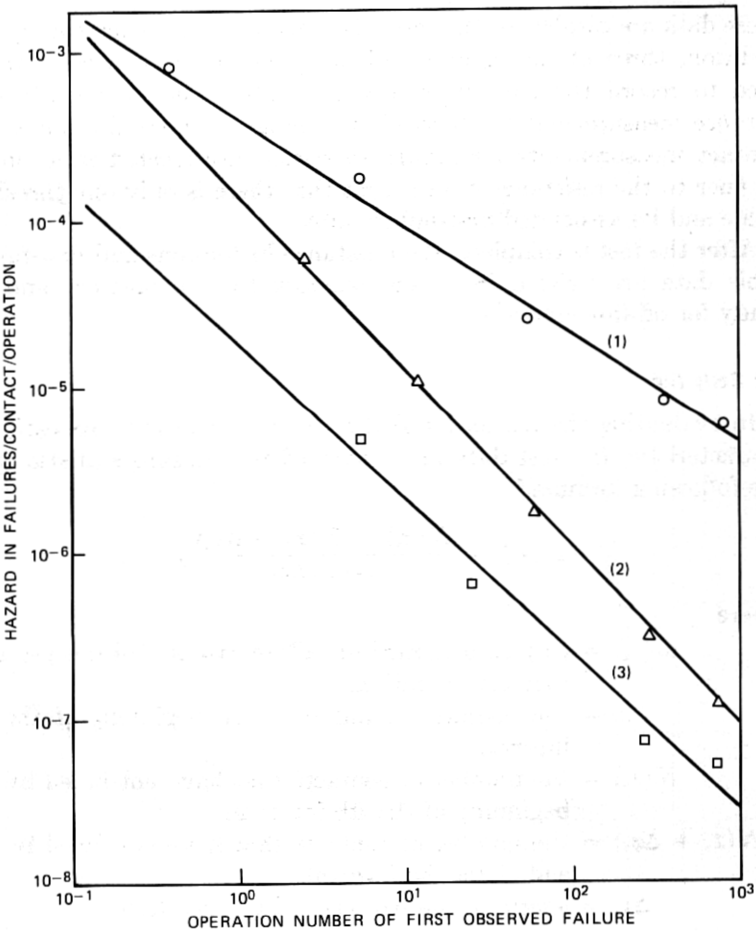

Fig. 2—Screening data for remreed sealed contact: (1) 150-milliohm failure level, (2) 100-ohm failure level, (3) release failures (stuck contacts). Sample size: 158,738 contacts. Data are plotted at midpoint of selected interval.

tion written in the form:[4]

$$f(x) = Kx^m \exp\left[-K(x^{m+1})/(m+1)\right] \qquad (3)$$

Mode	m	K
Resistance > 150 milliohms	−0.68	4.34×10^{-4}
Resistance > 100 ohms	−1.1	1.56×10^{-4}
Sticking	−1.0	3.12×10^{-5}

The Weibull distribution was not used in two of the three cases shown because the requirement for m was not satisfied.

Before continuing, some additional information about Fig. 2 would be useful. In the first place, a contact resistance which just exceeds 150 milliohms probably will not be detected by the No. 1 ESS system and, hence, it will not be removed from the system. In fact, in some cases, the 100-ohm contact could go undetected. However, the hazard is that such high contact resistances are prone to generate noise from mechanical disturbances and this could impair service. An additional point is that the interpretation of the hazard statistic assumes that once a contact failure is observed, that contact remains a failure for each succeeding operation. Data showing persistence of failure of sealed contacts indicate that this assumption is violated a high percentage of the time. Presently, software and data-handling routines are being developed to gather and analyze multiple-failure data. For the present, and since the first-failure event does not imply failure on all succeeding operations, this assumption is believed to be a good approximation and will be used.

Sealed-contact failure due to sticking is another matter. When a sealed contact sticks, it produces a circuit malfunction which is detected and an error message is printed on the No. 1 ESS teletypewriter. A sealed contact which persists in the stick-failure mode will cause an error message each time the system detects the circuit malfunction. Under these conditions, the sealed contact will probably be replaced.

This evaluation leads to the conclusion that the early failure modes describe a type of early failure behavior of the contacts with decreasing hazard as a function of contact operations. A study of the number of expected contact operations as a function of contact-circuit application yielded a wide-ranging distribution which had its 50-percent point at 1.25×10^4 operations per year. This result, together with the above test results, means that after six months of service, the expected hazard for the two resistance levels and the stick modes are 1.1×10^{-6}, 1.04×10^{-8}, and 5×10^{-9} failures per contact per operation, respectively.

A study of the effect of the large range of the expected number of contact operations together with the decreasing hazard shows very little difference in the performance of the sealed contacts after the first six months of service. The reason that this result is obtained is that the higher hazard (due to fewer operations after six months) is multiplied by a lower yearly operation rate.

2.3 End-of-life

Life testing was conducted in such a way as to accelerate wear-out mechanisms. Two types of failure modes existed during these tests: high resistance due to contact erosion and failure to release (or sticking). Contact erosion was accelerated by using a charged, twisted-pair cable to produce a low-energy-arc discharge, which causes a transfer of metal from one reed to the other. The acceleration results from a discharge occurring on each operation, and since the polarity of the charging voltage is fixed, the metal transfer is always in the same direction. In service, arcing does not occur every operation and the polarity direction tends to be random. After thousands of discharges, sufficient metal has been transferred so that the contacting surfaces become base-metal surfaces. The result is an increase in contact resistance.

The stick-failure mode is accelerated by magnetostrictively scrubbing the contact surfaces every 2000 operations. This is accomplished by operating each contact and then cycling the coil-drive current between a full saturate value of 210 ampere-turns and zero ampere-turns. Five cycles at one cycle per second are used.

Figure 3 shows a hazard plot for three contact-resistance-failure levels as a function of contact operations. The contact-resistance curves in the wear-out region have the characteristic shape of the log-normal distribution and in the early-life portion of the curve, the Weibull distribution. The useful-life portion of the curve lies below a failure rate of about 1.6×10^{-8} per operation for the 1.0-ohm level.

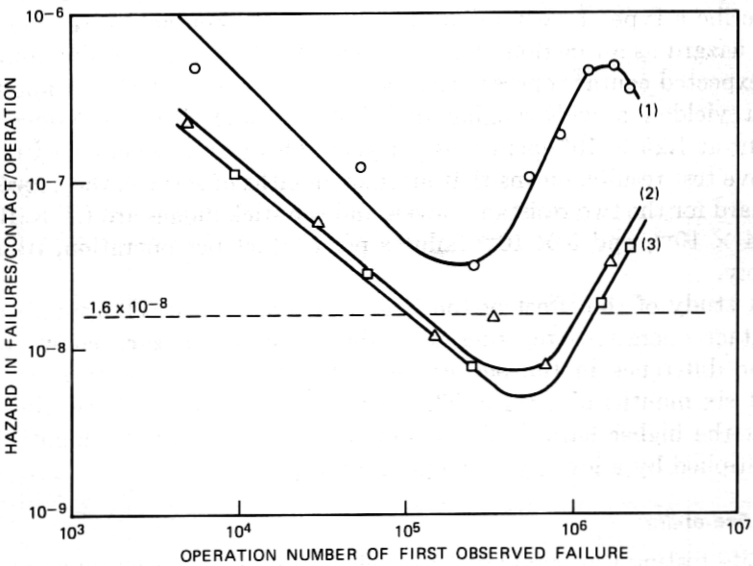

Fig. 3—Life test data for remreed contact: Failure rate vs operation number of first-observed failure for (1) 150-milliohm resistance level, (2) 500-milliohm resistance level, and (3) 1 ohm resistance level. Sample size: 456 contacts.

Since, in the field, erosion does not occur on every contact operation, the above rate is a conservative estimate. Nevertheless, these data lead to an estimated failure rate of about 18 FITs per contact during most of the life of the contact. It should be pointed out that even at the higher expected operation rates, the 1-ohm-failure data suggest that several years of use are required to reduce the failure rate to this level. No estimate of failure rate for the contact-stick mode was made from the data gathered during contact tests, because the magnetic field distribution of the test coil does not simulate the magnetic field found in the remreed switch crosspoint.

III. REMREED SWITCH

The remreed switch was evaluated with respect to thermal and mechanical environments. The purpose of the evaluation was to determine if the structural integrity and performance of the switch are satisfactory with respect to the extremes of these environments. Such conditions can occur during handling, transit, and service conditions. During testing, the limits of the expected environments were increased in an effort to accelerate the processes of degradation and aging. In all cases, caution was exercised such that unreasonable changes or new failure modes were not introduced.

Finally, in addition to thermal and mechanical evaluation, the remreed contact was investigated for sticking tendencies within the normal crosspoint environment. The sticking mechanism was accelerated by frequent magnetostrictive scrubbing.

3.1 Mechanical environment

The mechanical environment to which equipment may be subjected consists of shock pulses and vibrational stresses induced during handling and transit. Generally, the maximum shock and vibration inputs occur in the nonoperating condition during commercial transportation.

To simulate the shock pulses and vibrational stresses that may be encountered in transit, the shock and vibration levels[5] listed below were employed.

Vibration	Frequency	Acceleration	Displacement
	7–500 Hz	Constant 1.5 g	Variable
Shock	Amplitude	Duration	Shape
	15 g 30 g	0.011 s 0.011 s	½ sine wave ½ sine wave

During the vibration testing, a remreed switch was vibrated in each of its three mutually perpendicular axes at a frequency sweep rate of one octave per minute. The response to the excitation was monitored with accelerometers placed on the switch. All resonant frequencies were sustained for fifteen minutes.

During the shock-testing portion of the evaluation, a packaged switch was tested six times in each direction of its three mutually perpendicular axes.

The samples tested were the 296-1B and 296-1C codes of remreed switches.[6] To determine structural and electrical stability of the designs, initially and throughout the study, visual examinations as well as measurement of the following electrical parameters were performed.

(*i*) Operate sensitivity.
(*ii*) Release sensitivity.
(*iii*) Contact resistance.

Studies of the remreed switch vibrated at the prescribed level revealed a fundamental resonant frequency of 75 Hz and a peak acceleration of 24 g's. This occurred when the switch was mounted with the shunt plate positioned horizontally and the excitation in a vertical direction. No damage of the switch components, including the contacts, was found after the vibration tests and there were no significant changes in the electrical parameters.

Next, the remreed switch was placed in its Styrofoam* shipping container and was subjected to the specified levels of shock and vibration. Accelerometer responses showed a reduction in peak amplitude to 8 g's due to the damping effects of the shipping container. No significant changes were observed in either the structure of the remreed switch or in the measured electrical parameters.

3.2 Thermal environment

The environments used consisted of temperatures and humidities which represented conditions beyond those normally encountered during transit and in service. The purpose of the test is to determine the ability of the remreed switch to withstand extreme environmental conditions as well as to accelerate potential failure mechanisms.

The environmental exposure was an accelerated test using the temperature and humidity extremes listed below. To restate for emphasis, these conditions are higher than those occasionally encountered.

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* Trademark of Dow Chemical Company.

1. Room Condition*
2. 150°F @ 5% R.H.
3. Room Condition
4. −40°F @ 5% R.H.
5. Room Condition
6. 150°F @ 95% R.H.
7. Room Condition
8. 35°F @ 95% R.H.
9. Room Condition

The remreed switch test samples remained at each of the conditions listed until the electrical parameters being measured had stabilized.

Results of tests conducted with early, nonproduction samples indicated that some areas of thin plating on the ferrous metal parts led to corrosion spots. This was investigated and corrected in production samples.

Exposure of a 296-1C code remreed switch to the prescribed temperature and humidity caused no serious degradation of the materials of the switch. With respect to the electrical parameters of the switch, no problems were observed as a result of exposure to the experimental conditions; however, because of the possibility of changes in contact resistance at the low-temperature condition, operation of the switch below 32°F is not recommended.

3.3 Contact sticking in the remreed switch

This section documents results of a contact-stick evaluation of five 296-7A preproduction remreed switches. This particular switch design was used because of the ease of detecting and identifying a stuck contact. The design, called the 7A package, was intended for a signal-distributor application and has one lead of each contact brought out to a front or rear connector pin such that a one-for-one correspondence exists between connector pins and sealed contacts. The package contains two 8 × 8 arrays of crosspoints with two contacts per crosspoint and, as far as the contacts are concerned, it is identical to the other remreed switches.

To perform this evaluation, a special computerized test set was constructed. It contained a parallel 16-input solid-state scanner which was used to measure contact release time, a measure of sticking tendencies, to verify contact operation, and to sense stuck contacts. During the life test, every crosspoint of one 8 × 8 array was operated simultaneously with an LRC discharged current pulse. Next,

* Typically 74°F @ 40 percent R.H.

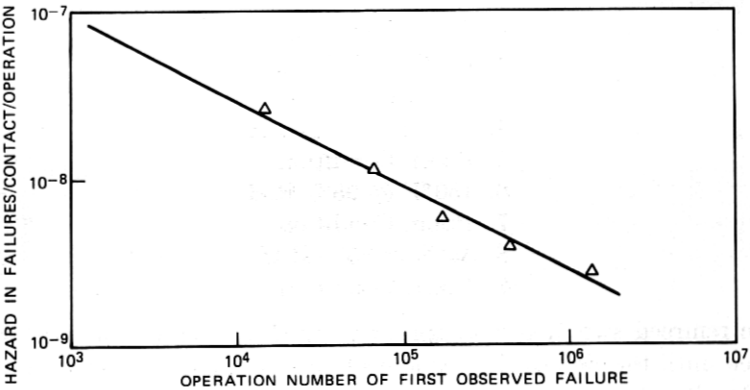

Fig. 4—Life test data for remreed switch: stick-failure rate per contact per operation vs contact operation number. There were three magnetostrictive contact scrub operations per operation. Sample size: 1280 contacts.

three more operate pulses were executed and the scanner was used to verify that all contacts had been operated. The three additional operate pulses produce magnetostrictive scrubbing. Finally, a release pulse was executed, one row at a time, and the release time was simultaneously measured for each of the 16 contacts in the row. If, after 5 ms, the contact was still not released, it was recorded as a stuck contact.

The stick data, plotted as stick failures per operation versus the number of contact operations, are shown in Fig. 4. The shape of this curve does not indicate that a wear-out mechanism might be commencing. Each of 1280 contacts was tested for 2×10^6 operations. A conservative estimate of the failure rate for the stick mode is 2.8 FITs. This is conservative because the remreed circuit design does not permit a crosspoint to be driven by consecutive, multiple operate pulses.

IV. CIRCUIT DESIGN

The circuit design adhered to a number of design principles aimed at ensuring that the devices were operated within their capabilities in order to maintain the validity of the reliability forecasts. These design principles include:

(*i*) Worst-case circuit design taking into account minimum and maximum battery and minimum and maximum temperature conditions as well as maximum circuit occupancy.

(*ii*) Derating of power and tolerance ratings of components to assure margin between the worst theoretical conditions and actual operating conditions.

The initial remreed controller design used only existing components and devices that had already undergone laboratory life testing to forecast reliability and, in many cases, had the benefit of considerable field experience in other systems. Subsequent design activity aimed at achieving further cost reduction has introduced some new devices designed specifically for remreed application. These are undergoing similar laboratory life tests prior to their introduction.

Laboratory tests were conducted with prototype and early production models to verify the margin and integrity of the design. These tests included simulated installation and traffic load runs in a No. 1 ESS system lab at elevated temperature (aisle ambient of 120°F) and minimum battery. The results of these tests were used by the designers to identify weaknesses and "fine tune" their designs.

Once the first remreed networks went into service, an extensive reliability study was undertaken to closely monitor performance. The study and some early results are reported in Section VI.

V. NETWORK MAINTAINABILITY

While failure rate is a measure of reliability, maintainability is also a measure of the ability of the design to provide the expected service. There are three principal techniques used in the remreed design to enhance network maintainability, given the forecasted device reliabilities described in Section IV. These are duplication, partitioning, and connectorization. The use of these techniques permits the system to meet its dual maintainability objectives: a loss of less than one call in 5000 and less than one hour of accumulated downtime per line in 40 years.

In general, all portions of the remreed network control that affect service to more than 64 lines or trunks are duplicated. Care has been taken in the design to assure that a failure occurring in one controller is isolated so that the system's fault-recognition-and-maintenance program can correctly switch in a working, mate controller.

The switching fabric (i.e., sealed contacts, switches, and associated wiring), as well as most of the pulse-steering PNPN transistors and diodes, are not duplicated. The approach taken here is to partition the fabric in order to minimize the effect of a fault on service. Most sealed-contact failures, for example, affect only isolated paths in the network and, therefore, create only a slight reduction in the network traffic capacity. Diode and PNPN transistor failures affect at most 64 lines or trunks.

All remreed apparatus is connectorized to facilitate replacement and minimize downtime. Most of the controller circuits, including all of the system bus interface, translators, and timing circuits, are mounted on plug-in circuit packs. The unduplicated switching fabric, pulse-steering diodes, and PNPN transistors are mounted in fully connectorized grid units.

VI. FIELD RESULTS

When the remreed quality study began on April 1, 1974, several hundred remreed trunk link networks (TLNs) had been shipped to the field. These networks contain over 30 million remreed sealed contacts, 1 million 1A silicon integrated circuits (SICs), 6 million 446F diodes, and 0.5 million 59A PNPN transistors.

The primary objective of the study was to measure the failure-and-replacement rates of in-service remreed apparatus. The study is fault-oriented, that is, attempts were made to analyze and understand each failure, why it occurred, how it was identified, and how it was corrected.

Secondary objectives included an evaluation of maintainability, identification of design weaknesses, and establishment of procedures for further studies on line link networks. Maintainability includes the effectiveness of diagnostic aids. One measure of diagnostic resolution is the number of packs replaced to clear a single fault.

The number of offices in the study was limited to seven to establish and maintain a good person-to-person working relationship with central office personnel. It was recognized at the time the study was organized that office-to-office variations probably existed and to measure this effect, offices of various sizes should be studied. Instead, for economic reasons, and since hardware variations were of greater importance, large offices were favored. In this way, it was hoped that a responsive arrangment to provide credible failure data would develop. Therefore, the following criteria were used to select study offices:

(*i*) The offices had to have large number of TLNs to maximize the total sample of TLNs in the study.

(*ii*) The offices had to have been in service at least five weeks to allow an operating base free of outside plant, trunk, and other system problems that might make it difficult to get reliable data on network performance.

(*iii*) The office had to have a history of good system performance (i.e., a sufficiently low level of error messages) to ensure that nonreliability problems had been cleared during the five-week period after cutover.

The study required a distinct sharing of responsibilities by Bell Laboratories, Western Electric, and the operating companies. Bell Laboratories furnished replacement parts, consulted with the operating company on special problems, and performed and coordinated analyses on all failed parts. Bell Laboratories then published reports on all data obtained.

The data-collection procedure used is shown in Fig. 5. Under this procedure the initial trouble is identified and cleared by the operating company craftsperson using normal procedures. Once a trouble has been cleared, the craftsperson prepares a trouble report and contacts the Bell Laboratories engineer. A parallel form is filled out at Bell Laboratories and a trouble number is assigned. The operating company then sends the suspect apparatus directly to Bell Laboratories and a

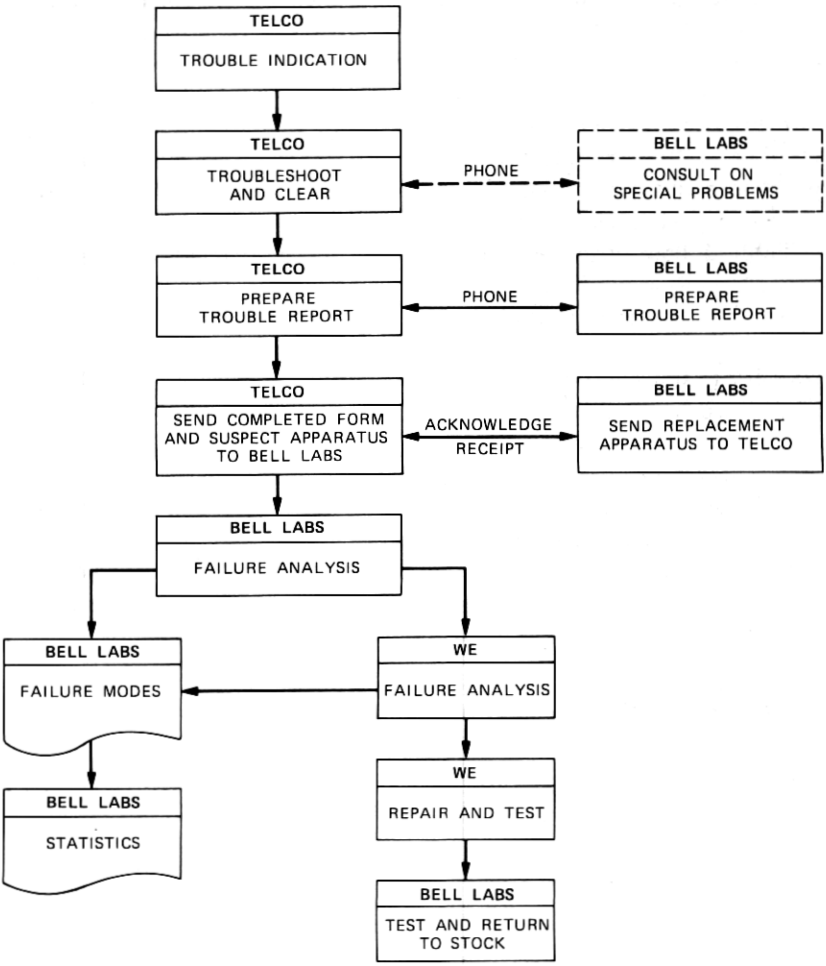

Fig. 5—Trouble analysis and evaluation procedure.

replacement is sent to the operating company. (This procedure ensures Bell Laboratories' participation in the failure analysis.)

The returned apparatus is matched up with its trouble report and tested in Bell Laboratories' systems laboratory and by Western Electric on standard factory test facilities. If the reported trouble is reproduced under test, the failing device is removed and sent to the responsible device organization for a more detailed analysis. In the case of multiple replacements, a careful analysis of the trouble report and the returned apparatus identifies the cause of failure. In such cases, the identified cause is counted as a failure, with the remaining apparatus counted only as a replacement whether damaged or not.

The detailed trouble report was valuable when difficulty was encountered in reproducing the reported trouble. Where the trouble report pointed to a device, a parametric analysis was conducted. In the case of grid failures, the trouble report enabled an individual sealed contact or printed wiring path to be analyzed. This practice led to a minimum number of "no trouble found reports". In the few cases where the problem could not be identified, the suspected apparatus was returned to the operating company and retested in its original location.

Table I lists observed failure rates and 90-percent-confidence intervals along with other pertinent information after 18 months of field monitoring for several devices. The study showed that the confidence intervals for the 446F diode, the 59A PNPN transistor, the 66S transistor, and SICs fell below the expected failure rate. The observed confidence interval of the 238A sealed contact matched the expected failure rate. However, the observed rate is lower than predictions based on accelerated laboratory tests. (The expected failure rate of one to two FITs is taken from a previous field study of 237B sealed contacts in No. 1 ESS working systems.)

Since the quality study produced failure-rate estimates periodically through the term of the study, time-dependent reliability information was obtained. An example of such information for 238A sealed contacts

Table I — Results of the trunk link network quality study

Device	Cumulative Device Hours	Expected* Failure Rates	Study Results		
			Observed	Lower 95% Confidence Limit	Upper 95% Confidence Limit
1. 238A Remreed Contact	3.1×10^{10}	1–2 FIT	1.6	1.3	2.0
2. 446F Diode	5.4×10^{9}		0.2	~0	0.9
3. 59A PNPN Transistor	5.3×10^{8}	20	5.7	1.5	14
4. 66S Transistor	8.6×10^{8}	30	14	8	23
5. SICs (137 type)	7.7×10^{8}	10	2.6	0.5	8

* Design information.

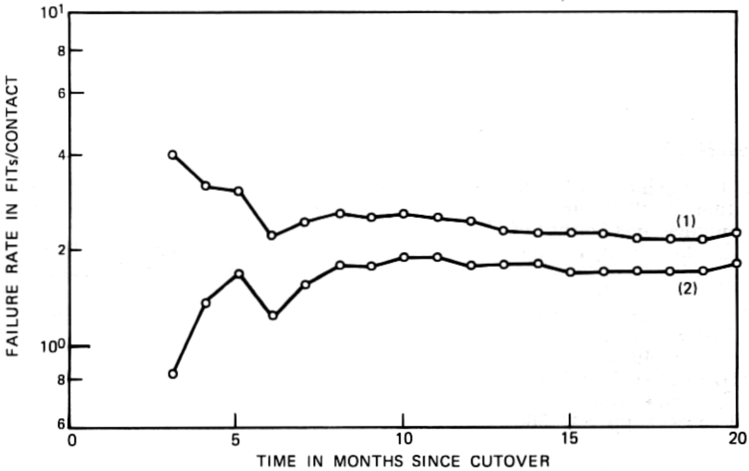

Fig. 6—Field-survey results of remreed contacts: time vs (1) upper 95-percent confidence level and (2) observed failure rate.

is shown in Fig. 6. Further analyses of the contact failures indicate that approximately 30 percent were due to sticking and 70 percent were due to high-contact resistance or contacts that failed to operate.

VII. SUMMARY

We have described in part some of the methods and philosophies of the evaluation program for the remreed contact and associated apparatus and equipment. For purposes of brevity and conciseness, the details of the tests were held to a minimum; additionally, many of the experiments performed in the course of remreed hardware evaluation were not mentioned. The several techniques used in these evaluations have been instrumental in achieving our high-reliability objectives: (*i*) large sample sizes were used to improve confidence, (*ii*) simulation procedures were employed to model the real world, and (*iii*) failure-mechanism acceleration was designed into the experiments in an effort to reduce study and testing times to manageable levels. In addition, a remreed quality study was instituted to verify that these objectives had been met.

VIII. ACKNOWLEDGMENTS

The authors wish to thank G. Haugk and E. G. Walsh for their continued support and productive discussions. To R. J. Gashler, P. W. Renaut, A. O. Johnson, and W. A. Liss go our deep appreciation for their frequent technical assistance. Grateful acknowledgment is given to the many operating company people at Bell of Pennsylvania, Illinois Bell, Michigan Bell, Northwestern Bell, Ohio Bell, South Central Bell, and Southern Bell who tirelessly offered their time and assistance during the field evaluation.

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