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Ten Years of Power Aging of the Same Group of Submarine Cable Semiconductor Devices

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The active devices in the first Bell System transistorized submarine cable system (SF) are unpassivated, diffused-base, germanium transistors and oxide-passivated, silicon diodes. At the date of this writing these devices have accumulated over 550 million device hours of powered operation in service and on the aging rack without failure or impaired device performance for a demonstrated failure rate of less than 0.00045 percent per thousand hours (4.5 FITs) with 90-percent confidence. This paper reports details of the behavior of 500 of these devices that have reached ten years of controlled power aging. The overall results indicate that initial reliability objectives are being achieved and that the semiconductor devices should not be expected to limit the desired life span of SF submarine cables.

I. INTRODUCTION

In the initial stages of the project, the decision to use germanium transistors in the first Bell System transistorized submarine cable was a rather bold gamble to take advantage of their then superior frequency capability while also attempting to mitigate any reliability inferiority to silicon transistors. When the decision was made, in the time period of 1960–61, silicon transistors were clearly the wave of the future and, although still inferior to germanium transistors in frequency capability, had already indicated their reliability superiority. Nevertheless, the results reported here, together with the results of regular aging and actual service experience thus far, offer rather convincing evidence that the desired reliability objectives are being achieved. The first submarine cable using these transistors, a relatively short cable with 136 repeaters, has been in service over eight years. A transatlantic cable with 363 repeaters has been in service nearly seven years. No semiconductor device failure nor degradation toward failure has yet been observed in any of the systems that have no redundancy and in which the failure of even

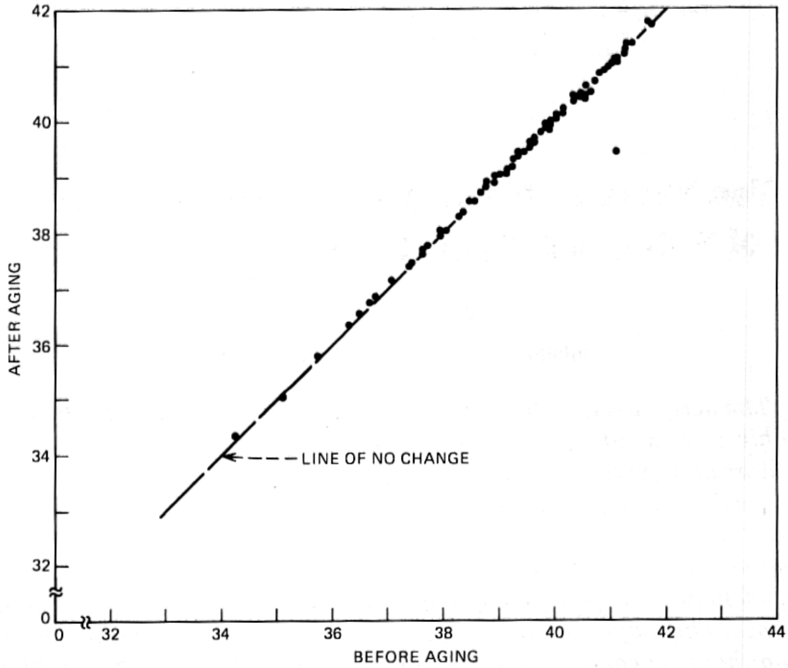

Fig. 1—Collector-base breakdown voltage in volts at 100 μA for L2287 transistors—before and after 10 years of power aging at 75 mW.

one device could disable the system. At the time of this writing the device-hours of service in these cables totals more than 250 million for both transistors and diodes. On the aging rack these devices have accumulated over 300 million device-hours of power aging—also without failure. On the basis of these results the demonstrated failure rate, with 90 percent confidence, is less than 0.00045 percent per thousand hours (4.5 FITs).

The method of providing semiconductor devices for the SF submarine cable system has been described previously.[1] As a further part of this program, a hundred devices of each of the five basic device codes of transistors and pn diodes have been retained on extended power aging. A milestone was observed in this program when the aging time on these devices reached ten years. The primary purpose of this paper is to show in a condensed way the behavior of these devices across ten years of power aging.

The transistors are of diffused-base germanium with no passivation or junction protection on the active chip. The diodes are of diffused silicon with grown oxide passivation over the junctions. All devices are encapsulated in hermetic packages.

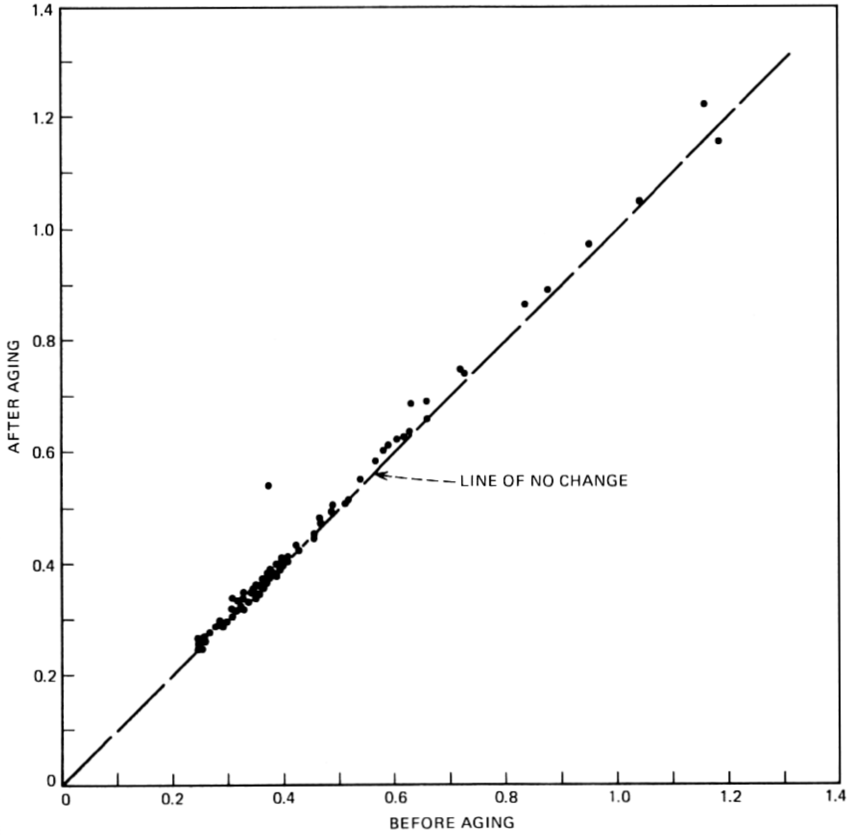

Fig. 2—Collector-base reverse leakage current in μA at 15 V for L2287 transistors—before and after 10 years of power aging at 75 mW.

II. DATA COLLECTION

All transistor parameters are measured before the devices are placed on long-term power aging, which is a period of about six months for candidate devices. From previous work with devices of this kind, we found that device current gain was the only parameter expected to show any consistent aging trend, and it is also the most critical parameter for the repeater amplifier circuit. For practical testing reasons during long-term aging, the dc current gain h_{FB} was measured. From the standpoint of the repeater circuit, however, the critical parameter is the low-frequency ac current gain h_{fb} rather than the dc current gain h_{FB}. The two are not the same, but they bear a relationship to each other, as described in any standard text on transistor theory. If one shifts, the other shifts in the same direction.

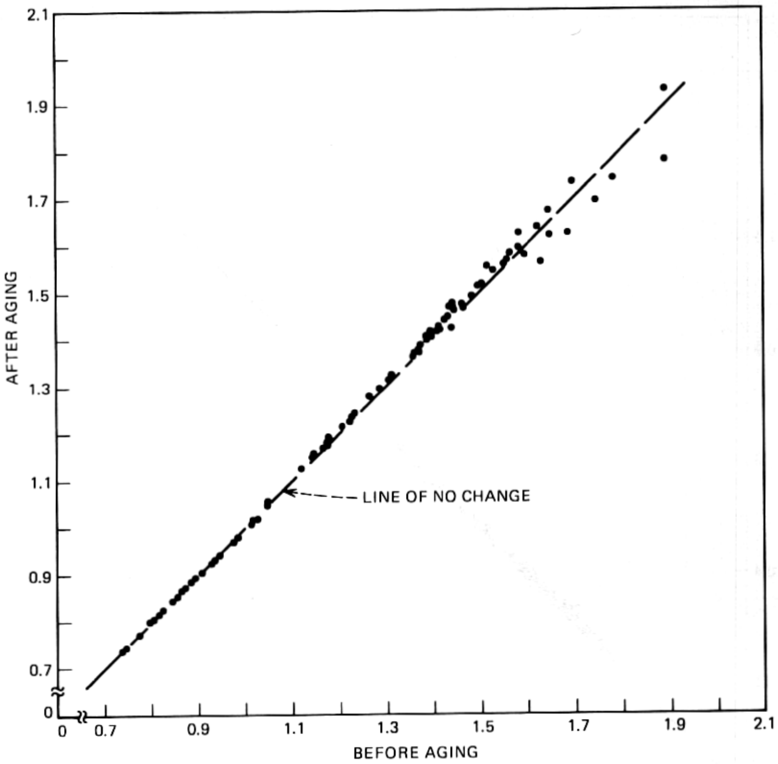

Fig. 3—Emitter-base breakdown voltage in volts at 100 μA for L2287 transistors—before and after 10 years of power aging at 75 mW.

Previous work with transistors of this kind had also indicated that any interruption of the bias on the device would cause the current gain to suffer a disturbance that would tend to obscure the real aging trend. For this reason, during long-term power aging, only the dc current gain was measured, and the measurement was made very precisely without disturbing the bias on the device. From the standpoint of device parameters directly relevant to circuit performance, therefore, the complete picture of the aged transistor cannot be known until the device is removed from long-term aging and all device parameters have again been measured. For such transistors, the aging time interval is ten years rather than six months.

Since the aging trends of diode parameters were not disturbed by change of electrical bias for testing purposes, most of the sensitive diode parameters were tested during aging. The diodes, therefore, were not removed from the aging rack at the end of the ten-year aging time. Interim aging information on these diodes has already been published.[2]

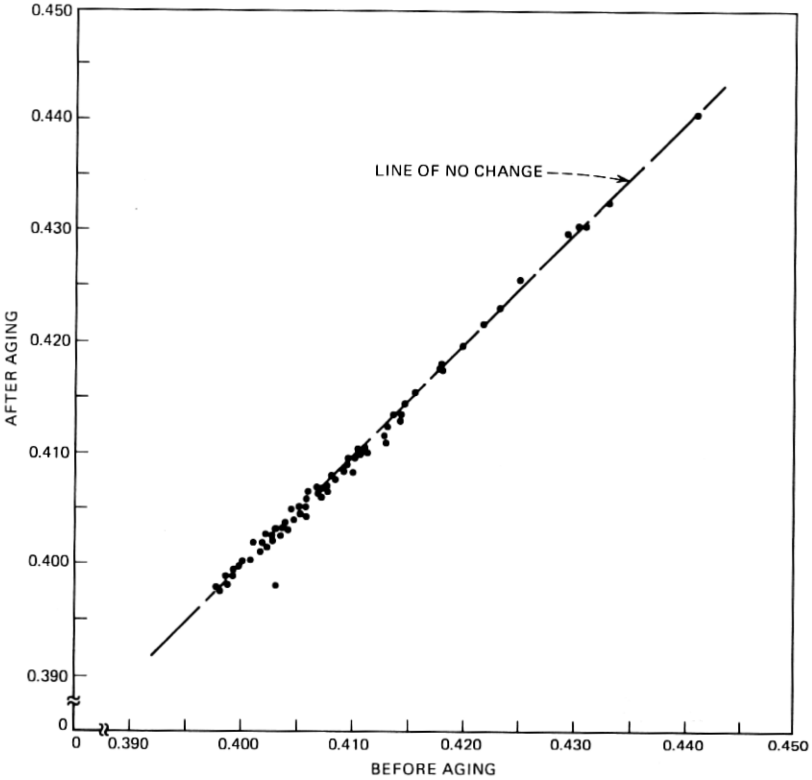

Fig. 4—Emitter-base forward voltage in volts at 15 mA for L2287 transistors—before and after 10 years of power aging at 75 mW.

III. PRESENTATION OF THE AGING RESULTS

A rather simple and clear picture of device aging behavior can be shown in the scatter plot in which the initial value of a device parameter is plotted vs the final value across the aging period for each device. For the transistors in this case, the information obtained at times between the initial and final values is not available for reasons discussed previously. For the diodes the information is available, but not significant since general aging trends, where they exist at all, are monotonic. For simplicity and consistency, therefore, all the ten-year aging results are shown here in the form of scatter plots.

IV. COMMENTS ON THE RESULTS

4.1 General

In most cases where any detectable parameter shifts have occurred across ten years of aging, the magnitudes of the shifts have been small

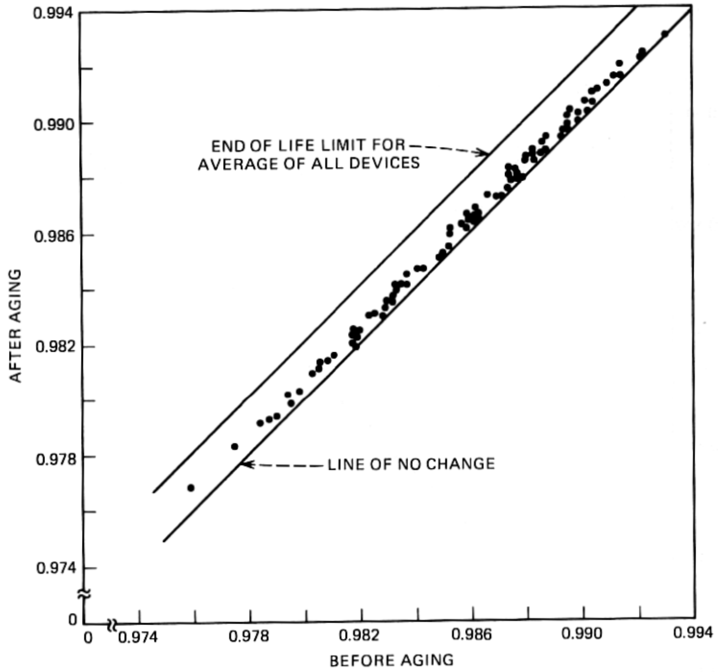

Fig. 5—Low-frequency common-base current gain for L2287 transistors—before and after 10 years of power aging at 75 mW.

and very uniform among all the devices, almost as if the devices had shifted in unison. Such behavior immediately raises the suspicion that the apparent shift may actually be an offset in testing rather than a real

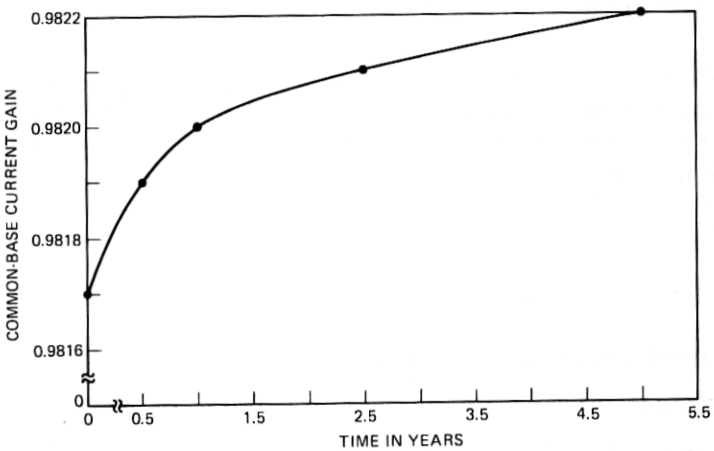

Fig. 6—Typical behavior of dc common-base current gain for diffused-base germanium transistors on long-term aging.

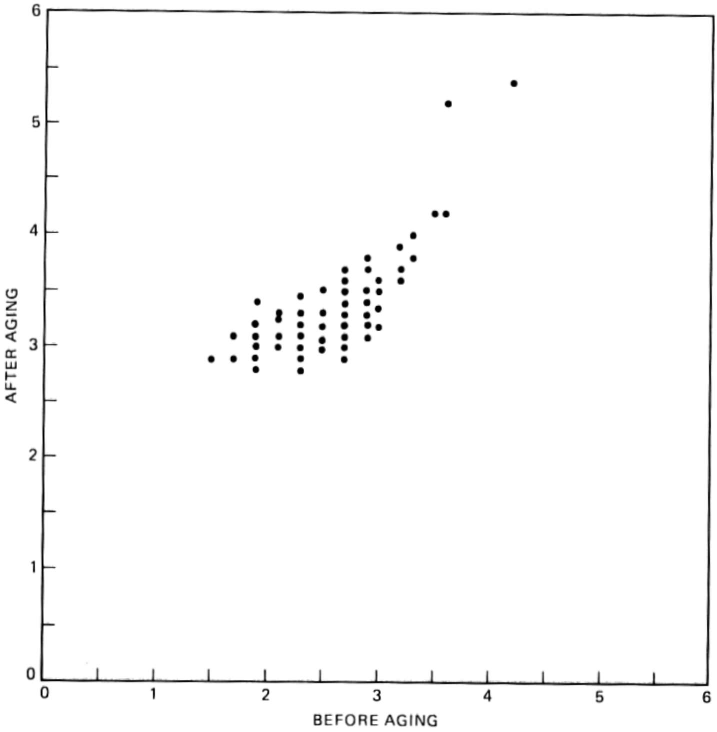

Fig. 7—Noise figure in dB at 5.5 MHz for L2287 transistors—before and after power aging at 75 mW.

shift. Unless the testing offset can be definitely confirmed, however, the shift must be accepted at face value. In the latter case, the uniformity of the shift makes the extrapolation very simple for more devices and longer time. The extrapolated result is then quite obvious and comfortable. Possibly the only deviation from this situation is the behavior of the leakage current of the L2320 diodes. Further discussion of this case follows under the heading of that particular diode.

4.2 L2287 transistors

L2287 transistors are split into 38A, 38B, and 38D codes for use in the first two stages of the amplifier and in the oscillator of the SF repeater. The two amplifier stages operate at power levels of 25 and 75 mW, respectively. The oscillator operates at a lower power level. During aging, all of these devices are held at a power level of 75 mW, composed of 5 V and 15 mA. The extended aging program has included one hundred of these transistors.

As shown in Fig. 1, the collector-base breakdown voltage of these transistors showed almost no discernible change after ten years of power

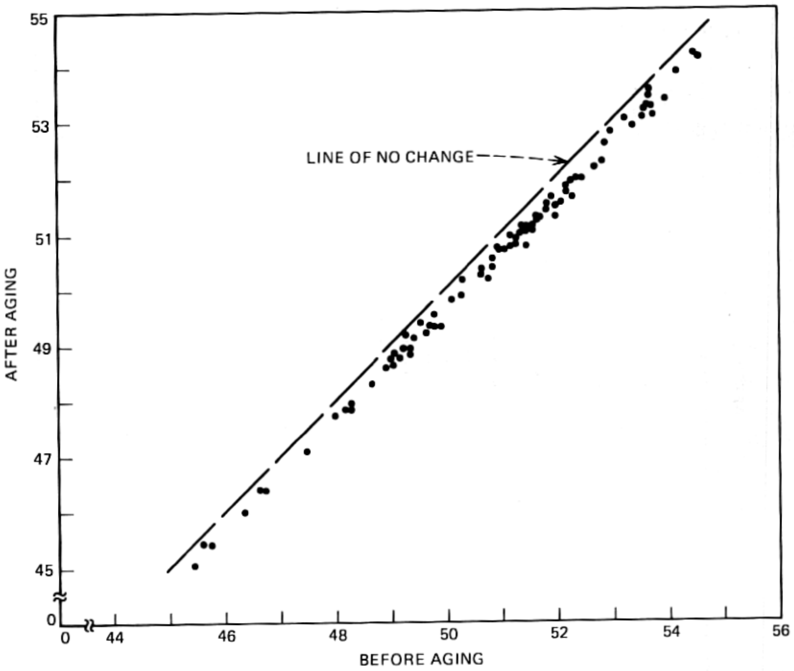

Fig. 8—Collector-base breakdown voltage in volts at 100 μA for L2288 transistors—before and after 10 years of power aging at 0.99 W.

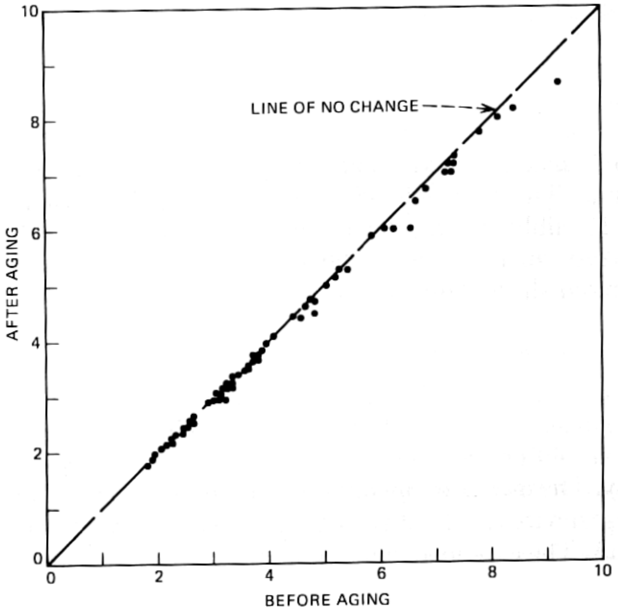

Fig. 9—Collector-base reverse-leakage current in μA at 15 V for L2288 transistors—before and after power aging at 0.99 W.

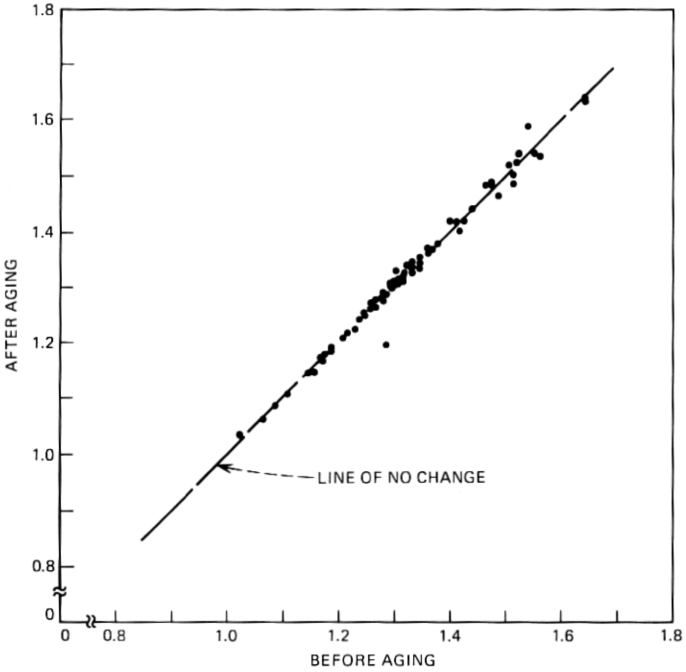

Fig. 10—Emitter-base breakdown voltage in volts at 1 mA for L2288 transistors—before and after 10 years of power aging at 0.99 W.

aging, with the exception of one device which showed a decrease of about 1.5 V. This device showed an increase in collector-base leakage current of about 0.15 μA, as seen in the lower part of Fig. 2, and a decrease in the emitter base forward voltage of about 5 mV, as seen in the lower part of Fig. 4. These changes, however, would have no effect whatever on the operational reliability of the device. No attempt has been made to determine the cause of the changes since all parameters of the device are still well within initial specification limits.

Figure 2 shows that the lower values of collector-base reverse-leakage current show no discernible change while those above about 0.5 μA show a very slight upward shift. Such a small shift, however, is of no practical significance.

The emitter-base breakdown voltages of most of the devices show remarkable stability, as depicted in Fig. 3. Only those above about 1.6 V show a small amount of scatter in the behavior. With the one exception, previously noted, the emitter-base forward voltages showed essentially no discernible change after ten years of power aging, as seen in Fig. 4.

Perhaps the most gratifying result of this extended aging program is the behavior of the low-frequency common-base current gain h_{fb}, as

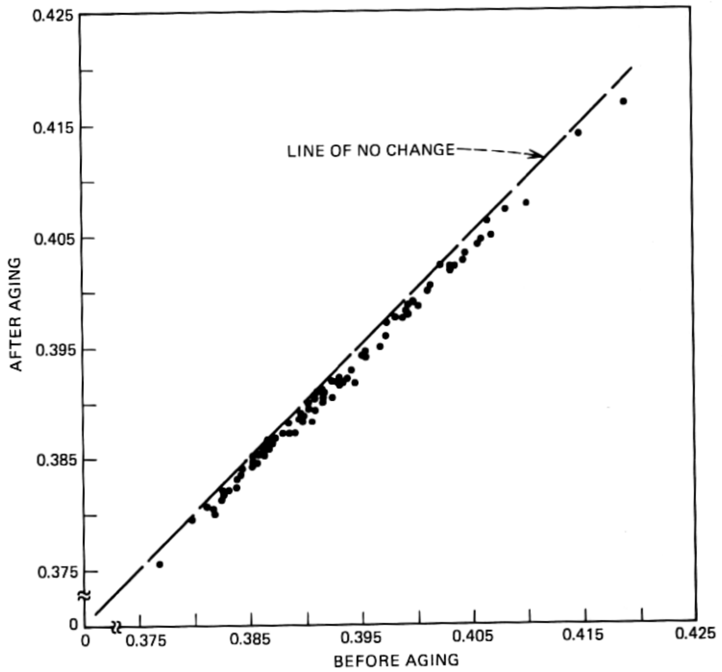

Fig. 11—Emitter-base forward voltage in volts at 90 mA for L-2288 transistors—before and after ten years of power aging at 0.99 W.

shown in Fig. 5. From the beginning, this parameter was expected to show a significant aging trend. Even under the conservative assumption that the aging of this parameter is linear with time, Fig. 5 indicates that in ten years of aging the average of the parameter has shifted only about a quarter of the way to end-of-life for the group. Actually, the aging of this parameter is known to occur at a decreasing rate with increasing time, as shown in Fig. 6 for a typical case of the aging of the dc common-base current gain. With similar behavior of the ac common-base current gain, the end-of-life for the group of devices would appear to be at some indeterminate time far beyond forty years.

Only one-third of the L2287 transistors (those for the first stage of the amplifier) are required to meet the initial noise figure specification limit of 4 dB at 5.5 MHz. Figure 7 shows that in fact nearly all of these devices still meet this limit after ten years of power aging. In the evolution and refinement of techniques for measuring the noise figure over the ten-year period of extended device aging, it was more important to provide the best and most realistic noise figure data than to maintain reference to the past. Other experience in aging indicates that if the other device parameters remain well-behaved, the noise figure does not change.

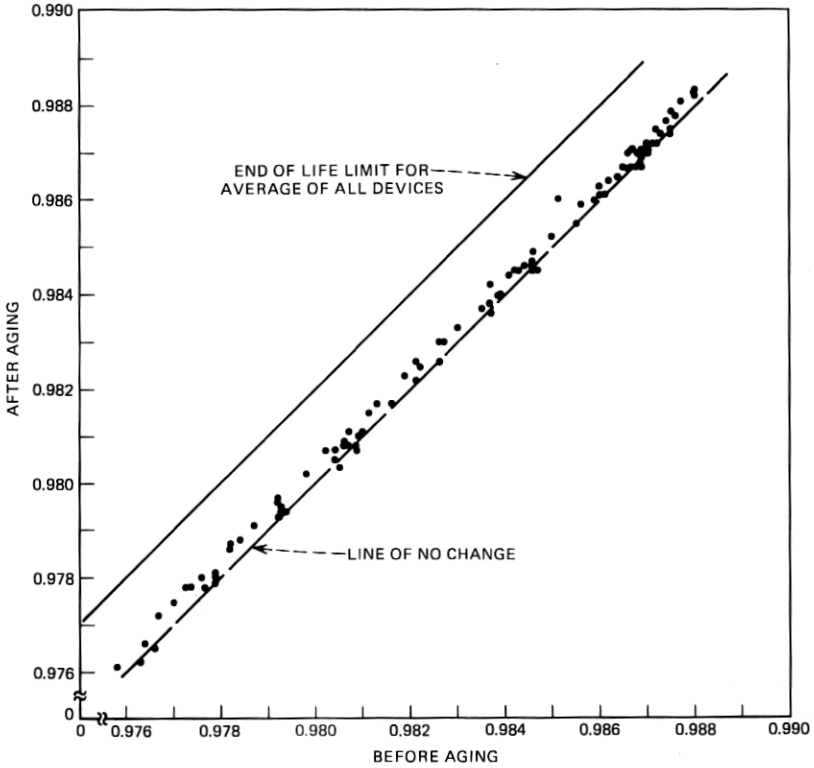

Fig. 12—Low-frequency common-base current gain for L2288 transistors—before and after power aging at 0.99 W.

4.3 L2288 transistors

The L2288 transistors, coded as 38C and operating at a power level of 0.99 W, are used in the output stage of the amplifier in the SF repeater. During aging, all of these devices are held at this same level of power, composed of 11 V and 90 mA. The extended aging program has included one hundred of these devices.

Figure 8 shows that the collector-base breakdown voltage of these transistors has very uniformly shifted downward by about a quarter volt after ten years of power aging. This is the kind of result which arouses suspicion that the apparent shift may actually be due to an offset between tests conducted over ten years apart. However, since the fact of testing offset could not be definitely established, the shift must be accepted at face value. Even if it is real, such a shift is of no practical significance. Under a simple linear extrapolation the voltage would be decreasing at the rate of 1 V in forty years, and a decrease of at least 30 V would be required before even the first device would begin to impair system performance.

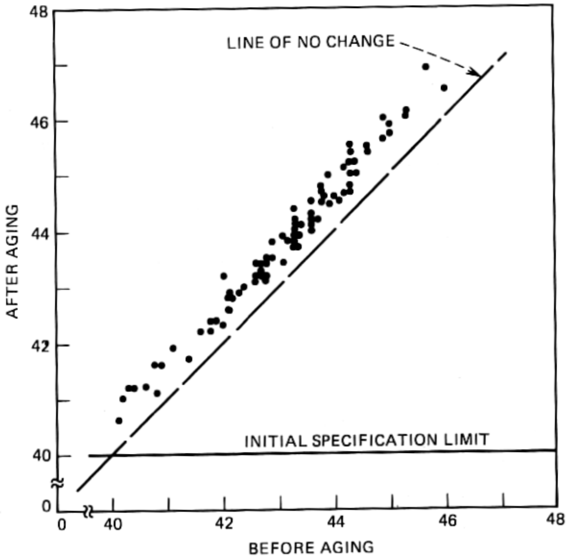

Fig. 13—Second-harmonic distortion in dB below fundamental for L2288 transistors—before and after power aging at 0.99 W.

In Fig. 9 the lower values of collector-base leakage current (below about 4 μA) show no discernible change after ten years of power aging. Those above about 4 μA show, if anything, a very slight decrease.

The emitter-base breakdown voltages shown in Fig. 10 indicate very consistent behavior, with the possible exception of one device whose voltage decreased by about 0.1 V and another whose voltage increased by about 0.05 V, again with no significant effect on circuit or system reliability since the emitters are always forward biased.

The emitter-base forward voltages shown in Fig. 11 indicate a small but consistent decrease of about 1 mV after ten years of power aging. Such a decrease is not significant enough to argue about whether it is real or an offset in testing.

The behavior of the low-frequency common-base current gain shown in Fig. 12 is again very gratifying. An increase in this parameter was expected, but the magnitude of increase has turned out to be smaller than expected. If the first ten years of aging serve as any indication, the end of life limit as an average for all devices will probably never be reached for all practical purposes.

Harmonic distortion for these devices was determined by measuring the level of the second and third harmonic at the output with a sine wave input at a frequency of 1.0 MHz at a power level of 5.0 dBm. Measurement precision is not in the same class with that of the dc and low-frequency parameters, especially for the initial data. During the ten-year

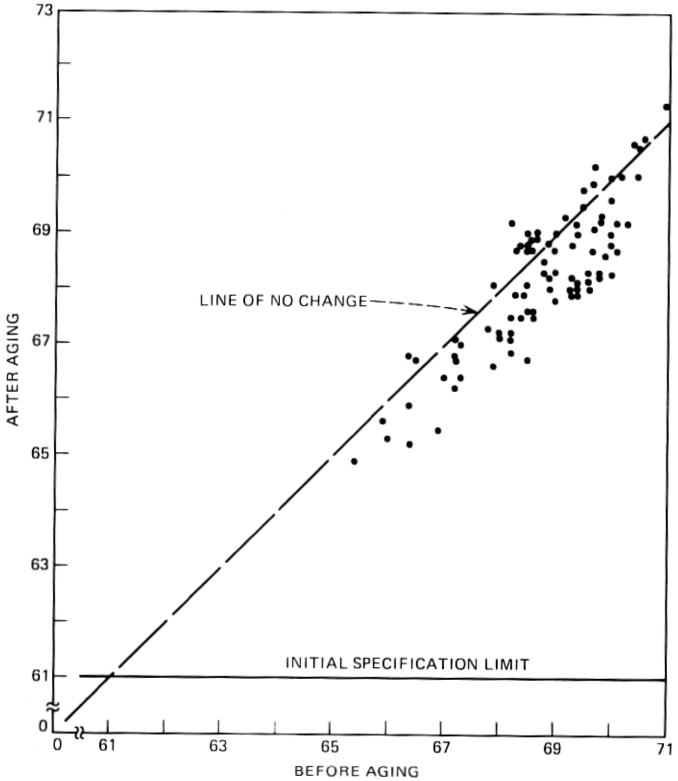

Fig. 14—Third-harmonic distortion in dB below fundamental for L2288 transistors—before and after power aging at 0.99 W.

period of extended aging, the precision of measurement was improved considerably. Nevertheless, the aging results shown in Figs. 13 and 14 should be considered merely indicative that the distortion parameters are quite well behaved and that after ten years of power aging, they still meet all of the device initial requirements.

4.4 L2317 diodes

The L2317 diodes, coded as 467A, are large area pn junction protective devices used in the power path of the SF repeater. During normal system operation, each device merely draws reverse-leakage current. In the event of a cable fault, however, it would conduct a large transient of reverse current to protect the repeater circuit from excess voltage. These devices are aged with 13-V reverse bias, which is a few volts below breakdown. Although the ten-year aging results are again presented in the form of initial and final values for each parameter, a large number of interme-

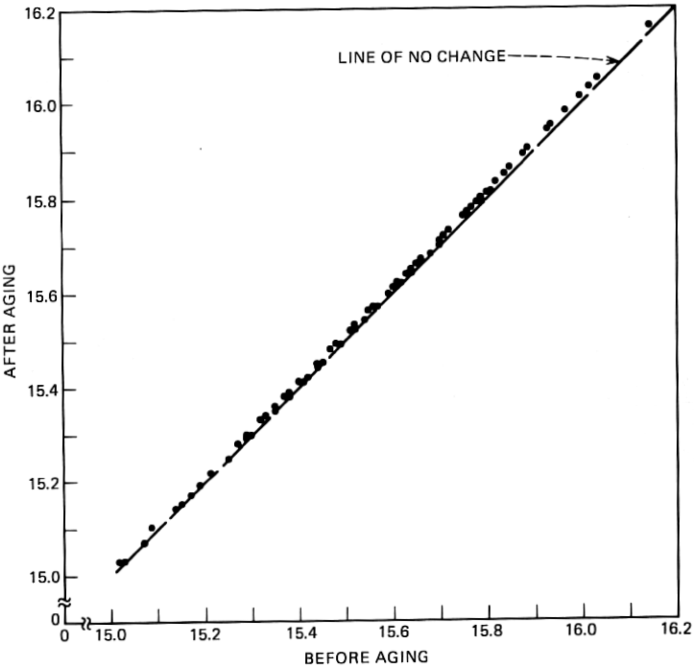

Fig. 15—Breakdown voltage in volts at 1.0 mA for L2317 diodes—before and after 10 years of power aging at 13 V reverse bias.

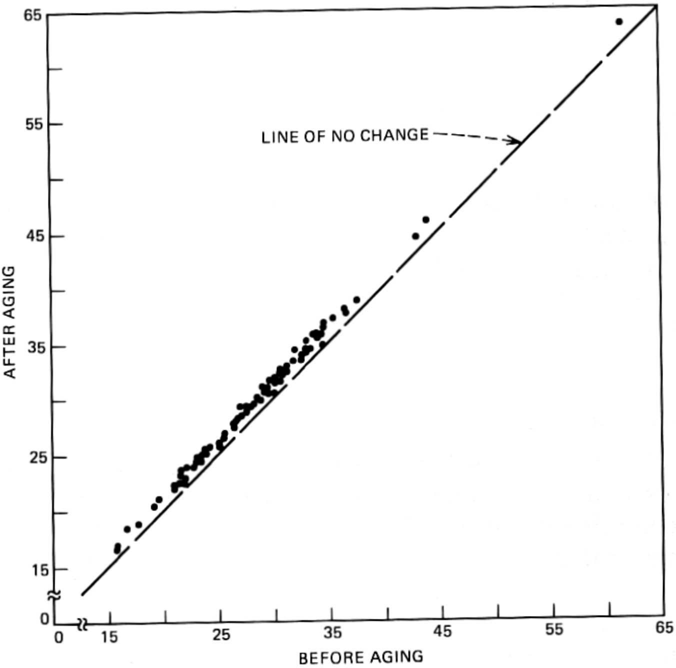

Fig. 16—Reverse-leakage current in nA at 13 V for L2317 diodes—before and after 10 years of aging at 13 V reverse bias.

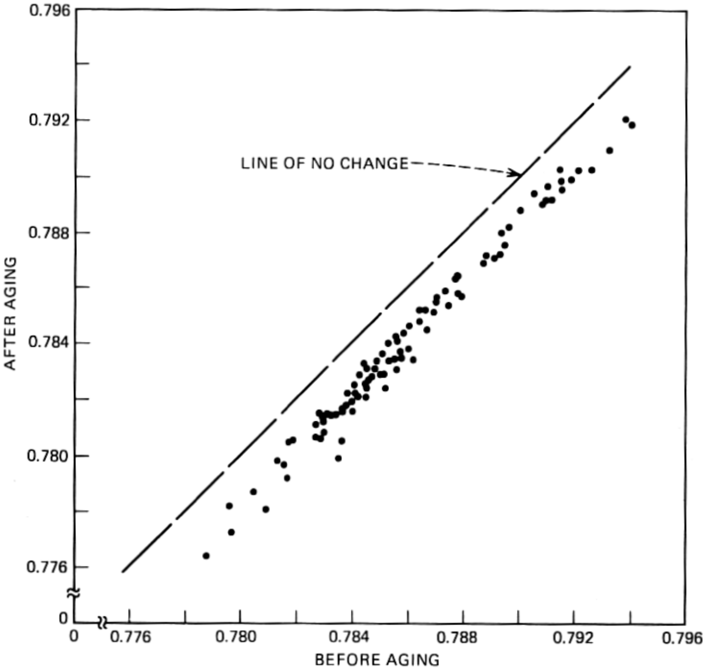

Fig. 17—Forward voltage in volts at 500 mA for L2317 diodes—before and after 10 years of power aging at 13 V reverse bias.

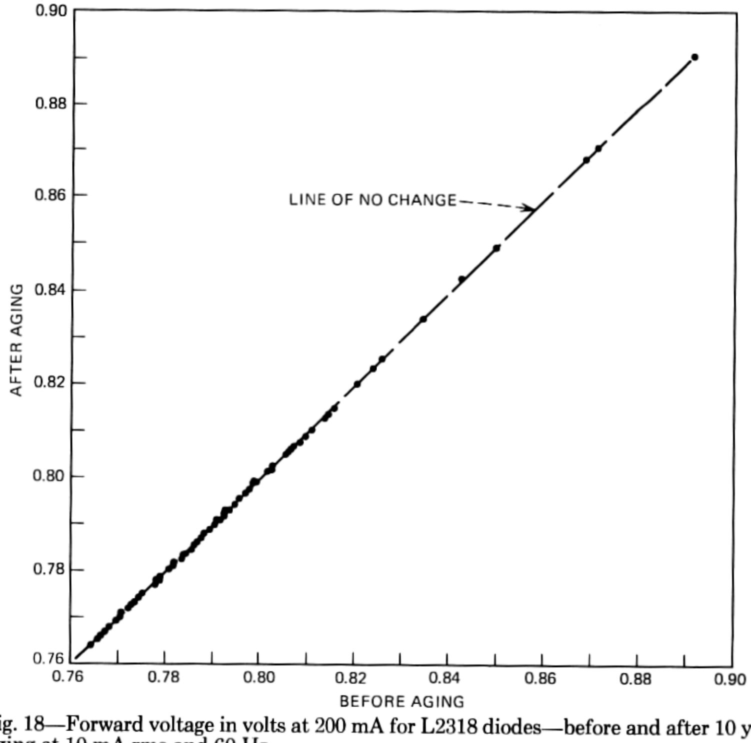

Fig. 18—Forward voltage in volts at 200 mA for L2318 diodes—before and after 10 years of aging at 10 mA rms and 60 Hz.

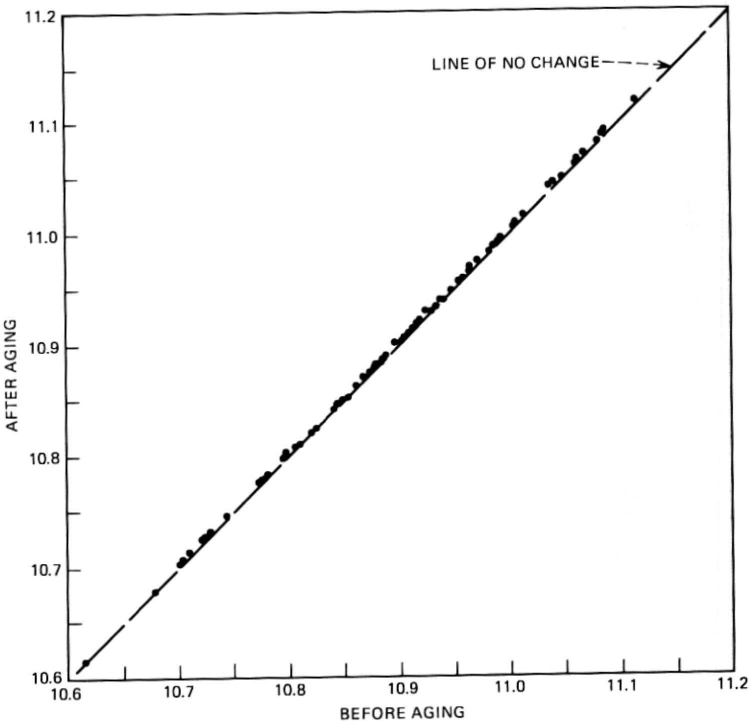

Fig. 19—Breakdown voltage in volts at 2 mA for L2320 diodes—before and after 10 years of aging at 2 mA in breakdown region.

diate data points taken during the ten years show no significant excursions away from the end points shown.

Figure 15 shows the behavior of the breakdown voltage of one hundred L2317 diodes across ten years of power aging. A very consistent upward shift of about 0.01 V is readily apparent but is too small to be of any practical significance. The behavior of the reverse leakage current shown in Fig. 16 also exhibits a small but very consistent upward shift of about 1 nA, while Fig. 17 shows a consistent downward shift of about 2 mV in the forward voltage.

4.5 L2318 diodes

The L2318 diodes, coded as 468A and 468B, are used for surge protection in the oscillator circuit of the SF repeater. Each device consists of two silicon pn junction diode chips mounted on a common metallic heat sink and oppositely poled so that only a forward characteristic is observed with an applied voltage of either polarity. During long-term power aging, a 60-Hz voltage is applied to make the diode conduct 10 mA rms in each direction. The forward voltage drop is measured at two

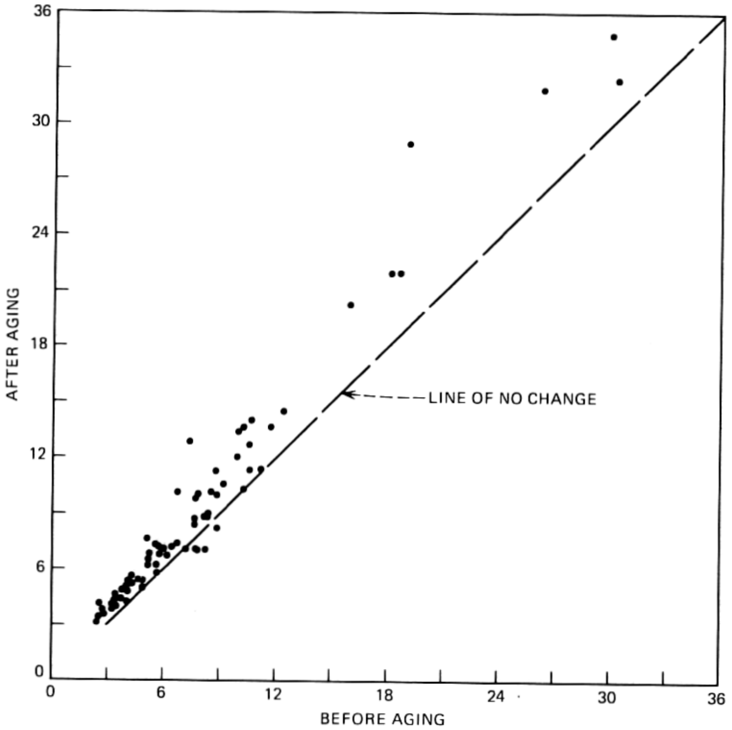

Fig. 20—Reverse leakage current in nA at 8 V for L2320 diodes—before and after 10 years of aging at 2 mA in breakdown region.

current levels in each direction during long-term power aging.

Figure 18 shows the behavior of the forward voltage of one hundred L2318 diodes in one direction and at one current level across ten years of power aging. No discernible aging can be seen. The behavior of the other forward voltages is not shown because they look no different.

4.6 L2320 diodes

The L2320 diodes, coded as 467B, are silicon pn junction limiter devices used in the third stage of the amplifier of the SF repeater. Operation is at 2.0 mA in the breakdown region, and the devices are aged under these power conditions.

Figure 19 shows the behavior of the breakdown voltage of one hundred L2320 diodes across ten years of power aging. No discernible shift in this parameter is evident.

In Fig. 20, a definite upward shift in the reverse-leakage currents can be seen. This is the one case where a significant amount of scatter is encountered in the magnitudes of the parameter shifts among the hundred devices. The data suggests that percent change rather than

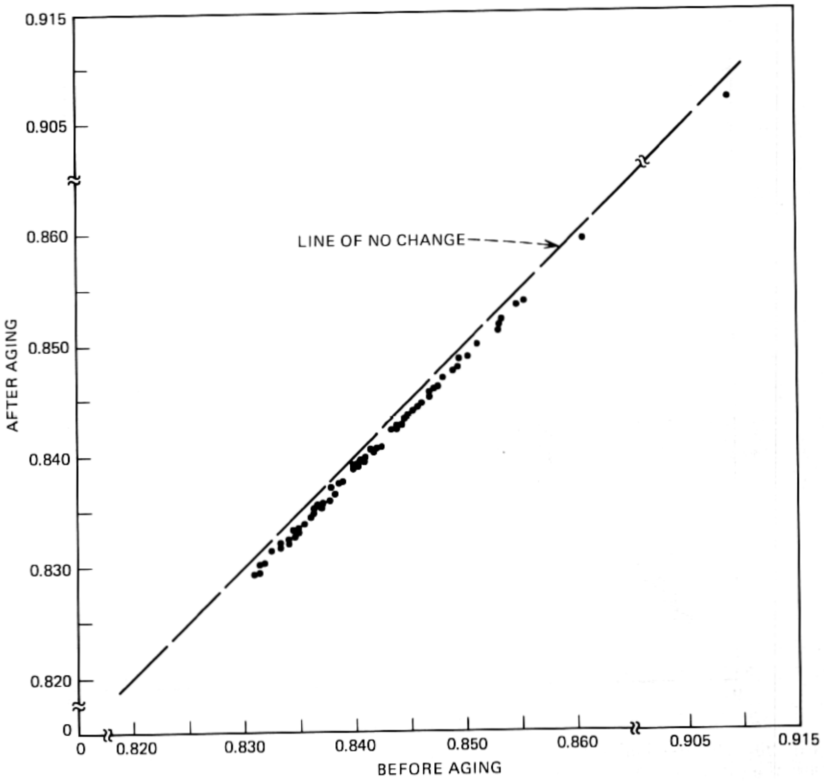

Fig. 21—Forward voltage in volts at 200 mA for L2320 diodes—before and after 10 years of aging at 2 mA in breakdown region.

incremental (delta) current change is probably the appropriate way to regard the behavior of individual devices. A leakage-current magnitude of at least 100 μA would be required in any one device to produce even the start of any impairment in circuit operation.

For this particular situation, even the aging of 100 devices for ten years still leaves some degree of uncertainty in how best to interpret the behavior in the tails of the distribution where the device would be found with potentially the greatest change in leakage current. In consideration of this situation and in consideration of the fact that a long cable might typically have 400 of these devices compared to the 100 shown here, it has been conservatively estimated[3] that with high (90 percent) confidence, a 100-μA leakage current would not be reached in any one device in less than 60 years.[3]

According to Fig. 21, the forward voltages of these diodes have shown a small but very consistent downward shift of about 1 mV in ten years of power aging. Such a shift is of no significance to system reliability.

V. GENERAL COMMENTS

The regular procedure for producing submarine cable semiconductor devices can be divided into three general stages: manufacturing, screening, and aging. A selection process is employed in each of these stages. The devices in this extended aging program progressed through the first two stages in the usual way, but did not have the benefit of having completed the standard aging stage of about six months with ensuing selection before beginning the extended aging period. Nevertheless, any of these devices, even after ten years of power aging, could still be considered candidates for cable use.

For the next generation of submarine cable (SG), the first of which was laid across the Atlantic Ocean in the early part of 1976, silicon transistors have been used throughout. Probably no new systems will ever be designed with germanium transistors. Nevertheless, the reliability record thus far of the germanium transistors used in the SF system is rather impressive in its own right.

VI. ACKNOWLEDGMENT

Over many years, a number of people contributed to this project. To list all of them would not be possible and to list only part of them would not be fair. Overall, however, the project stands as a shining example of team effort between Bell Laboratories and Western Electric.

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