Component Design, Construction and Evaluation for Satellites

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(Manuscript received March 11, 1963)

Components for a high-reliability system such as the Telstar project are obtained by:

(*a*) *design of the component for the required environment,*

(*b*) *careful control of manufacturing processes,*

(*c*) *elimination of potential early failures by screening tests, and*

(*d*) *selection of the most stable components.*

For passive components, these methods could be applied by using design parameters, suppliers and screening techniques established in the earlier submarine cable program, with consideration being given to the additional effects of the satellite launch and orbit environments.

Semiconductor component designs were selected by qualification tests using accelerated electrical and environmental stress conditions. Screening tests were applied to eliminate early failures, and resulting components were aged from two to six months before selection for the satellite. The recognition of the effect of ionizing radiation on transistors caused the addition of a radiation qualification test, or a screening to assure selection of the least sensitive devices. Tests have shown this screening to be effective for the radiation intensity expected.

Experience with the passive components, and evaluation of the accelerated test results and aging data of the semiconductor devices, indicate that the reliability objective was obtained.

I. INTRODUCTION

The importance of component reliability in the production of a successful electronic equipment of the complexity and with the reliability requirements of the Telstar satellite is well appreciated. Small systems and those of less complexity can be designed and built with special care, at reasonable cost, to have long life; large systems are subject to the laws of large numbers, which increase the probability of the malfunction-ing of at least one component part. Normal maintenance of large earth-bound systems may be economical, however, and system performance may be acceptable if malfunctions are not too frequent. In an orbiting satellite, on the other hand, the first failure must be at sufficiently great time to provide an economical system, and the component failures must therefore be sufficiently distant in time, or at a sufficiently low rate, to allow a practical design. This does not ignore the requirement that the circuit and equipment designs use the component characteristics to best advantage, and also protect themselves as much as possible against the probable modes of component failure.

Considerable experience has been built up in the Bell System on the use of parts of high reliability, a most easily recognized example being the long submarine telephone cable systems which at this date have had no failures in over 10^9 passive component hours and 5×10^7 electron tube hours of service.

The submarine cable repeaters, however, use specially designed and manufactured electron tubes and passive components. The design and selection of these were based upon many years of experience and life testing.[1,2] In contrast to this situation, the limited power available in an orbiting satellite and the severe limitation on total weight dictate the use of transistors as the active components, and in this case there is no extensive experience in a system of limited maintainability such as that of the submarine cable. Evidence is rapidly mounting, however, regarding the low failure rates obtainable with transistors in large systems, even without the use of special selection techniques. Transistors in large military systems have recorded replacement rates of 25 to 35 failure units,* and subsequent improvements in manufacturing processes show promise of failure rates appreciably below this figure. The sample calculations by I. M. Ross,[3] however, show that failure rates in the order of 10 failure units would be required even for a satellite system using only 140 transistors and 160 diodes in order to achieve a satisfactory probability of success for times appreciably beyond one year. Since the Telstar satellite circuitry requires a complement of about 1100 transistors and 1500 diodes, it can be recognized that failure rates better than 10 failure units would be desirable even for an experimental system. Similarly, since there are approximately 4700 passive components, capacitors, inductors, resistors and transformers in the satellite, these components must have an over-all failure rate of the order of 1 in 10^9 component hours if there is to be a high probability of success for a two-year experiment.

* A failure unit is defined as one failure per 10^9 component hours.

The immensity of the testing required to measure such low failure rates is difficult to comprehend and all but impossible to achieve in a limited time. For example, to provide 90 per cent confidence that none of the passive components in the satellite would fail in less than two years would have required that components of the same quality be tested until they had accumulated over 2×10^9 component hours without a failure. Even with the use of accelerated tests which, in the extreme case, might compress time by a 1000:1 ratio for some types of components, this amount of testing is prohibitive. Fortunately, other avenues are available which provide a basis for obtaining a high degree of reliability but with less assurance of its numerical value.

1.1 *Principles of Achievement of Satellite Component Reliability*

The principles and techniques originated for submarine cable components and now being applied to some of the complex missile systems were recently reviewed by J. A. Morton at the Eighth National Symposium on Reliability and Quality Control. These are, briefly:

(*a*) *Design of the component for the required environment.* This requires consideration of the possibility of actual "wear-out" of the component because of the environmental or life conditions. Even with the best design knowledge and perfect manufacture there may be fundamental limitations to the usefulness of a given material in its environment. Examples are the eventual evaporation of the oxide cathode in an electron tube and the limitation on the life of silicon solar cells due to radiation bombardment in space. If possible, with a proper knowledge of the operating and environmental requirements and of the capabilities of materials and processes, the designer should place this wear-out point well beyond the required useful life of the component.

(*b*) *Careful control of manufacturing process.* The relationship of quality control in manufacture to resulting uniformity of product and hence uniformity of response to operating environment can be readily acknowledged. This process control should be used to control all three phases of product life response: (1) it should prevent marginal product from extending the period of early failures due to manufacturing defects far into the useful life region, (2) it should assure low failure rates during the useful life, and (3) it should assure that wear-out failures do not occur prematurely, in the region of normally useful life.

(*c*) *Weed-out of potential early failures by screening tests.* It may be recognized that even in a product under careful quality control in manufacture there may be a certain percentage subject to early failure because of some defect not recognizable by the normal testing processes. Such defective units can usually be eliminated by means of rigorous environmental tests and by operating tests under conditions similar to that expected in use.

(*d*) *Selection of the most stable components of the population.* Even with careful quality control of the manufacturing process and with rejection of defective units through screening tests, there may still be expected a distribution of stability among the remaining units in the product. The state of the art of a given process required to obtain suitable operating characteristics may possibly result in variations of initial electrical parameters or in drifts or variations of these parameters with time. The careful observation of such parameters during the life test period may then allow the use of various selection techniques, more or less sophisticated as the requirements indicate, to obtain for actual satellite use those components least likely to fail in operation or to cause circuit performance changes.

The techniques of application of the principles of achieving reliable components will vary somewhat, depending upon the state of knowledge of design and processing, of testing and life evaluation methods and of circuit application factors. Because of the wide disparity of system experience with passive components and semiconductor devices, the following material will treat each of these separately.

II. PASSIVE COMPONENTS

Experience with passive components in submarine telephone cable repeaters has shown that this philosophy when applied to the selection, construction and testing of those components resulted in a highly reliable product. (Since in the systems made with such tightly controlled components there have been no component failures, for the present we can only say that there is a 70 per cent probability that the failure rate of the passive components does not exceed 1 in 10^9 per hour.) Similarly, experience and performance records with other Bell System and military projects has shown that some other types of components not used in submarine cable repeaters, when carefully manufactured and screened, are capable of this kind of performance. In a satellite these failure rates may be increased by unknown environmental factors, particularly the effects of Van Allen belt radiation and extreme shock or vibration during launch. Another liability for Telstar was a short schedule which required that screening tests, intended to eliminate potential failures, be limited to short-time tests, generally 100 hours or less. A further complication was the wide range of component types and values required.

These liabilities are offset to some extent by the fact that operating conditions of voltage, power dissipation and temperature are mild for the vast majority of the passive components. Thus the most likely causes of component malfunction are an occasional mishap in construction or some unforeseen effect of the environment or application. Consequently, with adequate derating to minimize the deteriorative processes resulting from load or voltage, the problem becomes primarily one of

(a) careful choice of components to minimize the effects of the environment,

(b) thorough inspection and screening to eliminate all components which may be subnormal in any way and thereby potential failures, and

(c) care in the physical application of the components to avoid compromising their integrity.

2.1 *Selection of Component Types*

The choice of the component types to be used was governed by a number of factors. One of the most basic and restrictive of these was that no new or untried types could be used. In other words, only those types which have been in widespread use for a period long enough and under a sufficient range of conditions to prove by field performance that they were capable of reliable operation, were considered for use. This restriction was also applied to the materials used in the construction of the components and to the details of construction so that both materials and the type of construction were well established and proven by field experience.

It is generally recognized that, especially under conditions of severe vibration or mechanical shock, adjustable components are less stable than their fixed counterparts. Consequently a strenuous effort was made to avoid the use of adjustable types. In most cases this was accomplished by selection from "post office" bins which covered the required range in suitably small fixed steps. Where this was inadequate, the over-all stability was enhanced by limiting the range of adjustable components to cover only the range between closely-spaced fixed steps.

It is easy to visualize the increased hazard of failure when conductors are made very small or dielectrics are unusually thin. Thus for extreme values of resistance the resistive film may be made so tenuous that at some points it is practically nonexistent, or for very low values the heavy deposit required to produce low resistance may be mechanically unstable. Similarly in capacitors, in an effort to crowd the maximum capacitance into a given space, factors of safety may be reduced, clearances may be made smaller, and physical damage to critical parts may even result. In addition to this degradation of reliability at the extremes of component values, it is not uncommon to find that characteristics such as temperature coefficient and stability with time or frequency are also degraded at extreme values. For these reasons the range of values, in a given physical size, was severely limited for the satellite components. This affected capacitors and resistors particularly, and in some cases limited the range of usable values to less than 15 per cent of the range of commercially available values.

Although the anticipated cumulative exposure to electron and proton radiation appeared to be well within the acceptable limit for most components, only the most resistant types were used. Thus hermetically sealed components filled with oils or electrolytes were avoided because such materials gas and build up destructive pressures under severe radiation. Structural and housing materials and coatings were also examined and chosen for their resistance to deterioration under radiation. These choices were based on the reported results of many studies, both within and outside Bell Laboratories, and on supplementary tests made in a Co^{60} cell on the specific types of components used in the satellite. Most of these were tests in which the components were subjected to load or voltage during radiation, and they were continued until the exposure exceeded by several times the maximum expected in service. From these tests it was concluded that radiation would not be the limiting factor in the life of the components, at least in a two-year experiment.

It was expected that, because of being sealed in the canister, the majority of the components would not be exposed to the extreme vacuum of space. All of the types, however — resistors, capacitors and power transformers — on which low pressure might have an effect were tested under such conditions. Furthermore, such components were rated so that they would operate under extremely low pressure without abnormal temperature rise or other harmful effects.

Even with these restrictions there were very few instances where suitable standard components were not available.* Table I lists the types of components used and their typical uses.

2.2 *Selection of Components for Specific Applications*

As mentioned above, the most likely causes of malfunction of components are misapplication and deviations from design intent during manufacture of the components. The term "misapplication" in this case

* Approximately 95 per cent of the passive components used were purchased outside the Bell System.

TABLE I—TYPES AND TYPICAL USES OF PASSIVE COMPONENTS

Use	Type	Number Used
	Capacitors	
General purpose, temperature compensation	Ceramic	814
Precision in low values	Glass	47
Precision in high values	Mylar*	18
High values, small size	Tantalum solid	444
Precise tuning	Glass and quartz tubular trimmers	20
	Resistors	
General purpose, low precision	Carbon composition	1325
General purpose, moderate precision	Pyrolytic carbon film	1414
High precision, high frequency	Metal film	136
High precision	Wire wound	44
Power dissipation	Vitreous enameled wire wound	30
	Inductors	
High frequency, general purpose	Nonmagnetic core, fixed; Nonmagnetic slug, adjustable	140
Power frequency	Permalloy dust core toroid	2
Memory coils	Ferrite core	230
	Transformers	
Narrow-band high frequency (tuned)	Nonmagnetic core, adjustable inductance; Magnetic core toroid	43
Broadband high frequency	Closed ferrite core; Ferrite cup core; Laminated magnetic core	15
Power frequency	Magnetic tape core toroid; Permalloy dust core toroid	6

* Registered trademark, E. I. DuPont DeNemours & Co.

is used in a broad sense to include improper voltage, temperature or wattage, or failure to meet circuit or ambient conditions, as well as the actual physical mishandling or incorrect mounting of the component. Since the components used were types known to be capable of reliable operation, the major problems were to assure their reliability by careful handling and use and to eliminate by thorough testing or screening those individuals which were abnormal in any way. An essential ingredient in any project requiring reliability in components is the care and perspicacity with which these factors of selection and use are examined. In these respects Project Telstar differed from other Bell System projects in degree only. Component engineers recommended types on the basis of circuit engineers' requirements and also prescribed conditions of use (handling, mounting, etc.). Subsequently the application was independently checked by a reliability engineer, who compared operating conditions with component ratings which were established especially for the Telstar program. In general, all components were derated at least 50 per cent from commercial ratings. During fabrication of all development, preproduction and final models of the Telstar spacecraft, all cases of malfunction which were in any way related to the components were examined and appropriate measures taken to avoid future difficulties. This procedure was particularly effective in eliminating misapplications and physical mishandling.

2.3 *Screening and Final Selection*

The testing or screening of components varied from type to type, but in general the bases for the tests were standard Bell System high-reliability specifications, which were supplemented by restrictions on materials and in some instances by additional requirements. In addition the suppliers were asked, and willingly agreed, to apply any additional tests or requirements which in their opinion would enhance the reliability of the product. Several such additions to normal processing were made, ranging from special handling to the imposition of short-time life tests or special electrical tests. Chief of the requirements added to the Bell System specifications was the assignment of an identifying number to each component and the recording of data for each numbered component at various stages of the test program. These data were delivered by the supplier with the components. On receipt of the components they were subjected to additional tests which ranged from a check of electrical characteristics to voltage or power aging supplemented by "before" and "after" measurements of all critical characteristics. All of the data, both the supplier's and the Bell Telephone Laboratories', were then analyzed either manually or by machine. The components to be used were selected by this analysis. Three criteria were used in this selection:

(1) fixed limits on critical attributes,

(2) stability of characteristics throughout the test period, and

(3) conformance with normal behavior.

Many of the requirements applied to conventional components have no direct relation to the performance of the circuits in which the components are used but are instead applied to control the quality, i.e., to insure the integrity of the materials and proper processing of the component. The same is true to an even greater extent when extreme reliability is required, so that every property which might have an effect on, or be a measure of, reliability is controlled. Table II lists the major kinds of requirements applied to capacitors and resistors. Some of these were applied only to certain types: for example, the X-ray requirement was used only on hermetically sealed designs where internal clearances and positioning could not be checked visually. Similarly the requirement for change under load was applied only to resistors intended to dissipate significant amounts of power. As shown in this table, the requirements for the Telstar satellite components covered much more than those attributes which were of importance from a circuit performance standpoint. An example of this is the application of requirements for ability to withstand atmospheric moisture. At no time during shipment, assembly into equipment, or use were the components subjected to severe humidity conditions, but tests were made to measure their ability to withstand such conditions. Since the normal product is capable of meeting these requirements, failure of the Telstar satellite components to do so would have indicated that the product was inferior to normal product either in its moisture protection or in contamination with moisture-sensitive materials. Similarly, voltage aging tests on capacitors and power aging tests on resistors were made at stress levels chosen to insure that the component quality was consistent with capability rather than just adequate for the stresses in service. Furthermore, these tests were made on 100 per cent of the product, and entire lots which had more than a few per cent of failures were rejected.

In the final selection of the components to be used the record of each one was scanned. Where there was a large margin between the component capability and operating conditions or requirements, practically all components which met the fixed requirements were considered qualified for use. In other cases where the margin between capability and use was

Table II — Types of Requirements Applied to Capacitors and Resistors

Resistors	Capacitors
Resistance	Capacitance
Aging resulting from load	Power factor
Aging resulting from temperature cycling	Insulation resistance (or leakage current)
Moisture resistance (sampling)	Dielectric strength
Change under load	Capacitance-temperature characteristic
Temperature coefficient of resistance	Voltage aging (100%)
	Life test (sampling)
	X-ray

smaller, only those components with characteristics near the norm and showing a high degree of stability were considered acceptable. Even when deviations from normal behavior were in the direction of better performance, those which showed abnormal deviations were rejected since this might be the compensatory result of two mechanisms, one of which could ultimately cause failure. As a result, the yield of acceptable components ranged from nearly 100 per cent of those received of some types to approximately 50 per cent of other types.

While the foregoing applies specifically to purchased components, the procedure for those few components made by the Bell Telephone Laboratories or Western Electric Company differed mainly in that their construction was under direct engineering supervision and inspection. This close supervision and detailed inspection is particularly important for some types of components, such as inductors and transformers, where tests to accentuate and uncover weaknesses are either destructive or nonexistent. In addition to this factor, manufacture of some components by Bell Telephone Laboratories or Western Electric was undertaken because of the need for special characteristics, unusually close tolerances on electrical parameters or unusual operating conditions. Examples are: very stable inductors with a narrow (2 to 3 per cent) adjustment range, others with inductance tolerances measured in millimicrohenries and unimpregnated capacitors for use at high voltages. The manufacture and testing of many of these were essentially laboratory operations, but even with this close control the components were screened by appropriate tests before being released for use. For example, the high-voltage capacitors used in the dc supply for the traveling-wave tube were screened by applying an overvoltage of 150 per cent of rating for eight weeks.

While these measures do not permit or lead to any quantitative calculation of the reliability of the components, past experience, coupled with engineering judgment of the effect of the special handling, leads to the belief that the passive components will achieve the low failure rate needed for successful conclusion of the Telstar experiment.

III. SEMICONDUCTOR DEVICES

As indicated previously, the number of semiconductors to be used in the Telstar experimental satellite dictated that the failure rate should be in the order of 10 failure units or less to provide assurance of reasonable life even for experimental purposes. The achievement of such reliability would require close attention to the principles outlined previously, and a program was established along these lines for selecting the necessary devices. In contrast to the situation on passive components, very limited experience was available regarding the specification of suitable procedures for manufacture or selection to the desired reliability. The reliability principles described in Section 1.1 can be applied, however, and the particular techniques of application are indicated in the following description of the semiconductor program.

3.1 *Component Design*

Table III shows the numbers of diodes and transistors required per satellite, the total number required for all satellite models and the number actually processed in the program. The total number of transistors and diodes was divided into 41 different basic types or prototypes, from which a total of 93 individual codes were selected to match the specific requirements of the many circuits. Although two types of diffused germanium transistors and three types of diffused silicon diodes were designed and manufactured for the Telstar satellite, the large number of other types and the total numbers required dictated that existing types in production be used where possible for this system, provided each had the basic design features necessary for reliability[3] and could also qualify for use in the specific intended environment.

A basic requirement of design-for-reliability is that there should not be any feature of the design which contributes the possibility of wear-out failure within the usable lifetime or which prevents the achievement of low failure rate during that time. Most of the types were selected from those previously designed for either military or Bell System use. The designs had already received consideration of possible wear-out failures and they had also met such design requirements as (a) high internal element resonant frequencies, (b) capability of withstanding storage temperature extremes and soldering temperatures and (c) adequate resistance to vibration or shock of typical applications.

Beyond these normal design considerations, it was additionally necessary to review the capability of each candidate type for operation in the satellite environment. This was accomplished by a number of design

TABLE III—*Telstar* SEMICONDUCTOR REQUIREMENTS

	Number per Satellite	Number of Types	Total Number Required	Total Number Processed
Diodes	1,521	18	12,526	28,525
Transistors	1,119	23	9,996	29,644
Total	2,640	41	22,522	58,169

qualification tests, as shown in Table IV. The requirements for these tests were established to exceed the specific conditions resulting from the satellite design or, as with some of the mechanical tests, to reconfirm the normal device design capability. For example, the temperature cycling extremes for the devices to be used in the electronics package were established by typical device capability even though the mechanical design of the package is such as to maintain its internal temperature at or near normal room temperature. The diodes used to isolate groups of solar cells, however, were to be mounted near the outer shell or skin and would be subjected to much more extreme temperatures; the temperature limits were established, therefore, to assure that no feature of the design would prevent proper performance at these temperatures.

Similarly, the vibration tests for most of the designs were established to assure performance in the electronics package at the low frequency of resonance determined by its mounting, using considerable margin in the acceleration level. The blocking diode design, however, was actually tested on a mechanical model of the Telstar satellite design in order to assure achieving the mechanical environment of the exact mounting location. The other conditions of centrifuge, shock and temperature-humidity cycling conform to typical requirements of handling, since the corresponding requirements of the satellite would be very mild.

The qualification of device types for reliability depended heavily upon the step-stress techniques[4,5] which determine the distribution of failures with increasing stress for a given time of application of stress. With this distribution obtained for several different times of application, a plot can be made of a relationship between time and the stress value at

Table IV—Design Qualification Tests

Mechanical	
Temperature cycling	
	−65 C to +85 C for devices in electronics package
	−120 C to +40 C for devices on skin
Temperature-humidity cycling	
Shock	2,000g, 0.2 msec
Centrifuge	5,000–10,000g
Vibration	100g, 80 cycles for devices in electronics package
	100g, 100–2,000 cycles for devices on skin
Reliability	
Accelerated tests	
Field experience	
Radiation	
Proton, electron and γ-ray exposure	

median failure. Either temperature or power, or both were used as the stress for each transistor or diode type in order to achieve extrapolations to the expected condition of use and to provide estimates of the failure rates to be expected. Generally the results were significant and satisfactory. One diode type was rejected from the program because of the very short median life indicated by the extrapolation of the step-stress data. Some of the microwave diodes, however, were not capable of accelerated stress testing because of their construction, and dependence was therefore placed upon the long history of satisfactory experience with these diode types in other transmission systems.

To qualify the designs for resistance to radiation, samples were exposed to proton and electron radiation, with electrical tests being made before and after exposure. No adverse response was indicated here except for germanium alloy transistors for power regulation, which showed degradation due to permanent damage in the germanium. These tests were augmented with γ-ray exposure (correlated to proton exposure) and sufficient data were obtained to establish the alloy transistor degradation rate. A shielding of about 0.120 inch of aluminum was used to reduce this rate to an acceptable value for the system life.

In addition to the design qualification testing, consideration was given to circuit application factors and to the effect of the environment on device capability as described for passive components in Sections 2.1 and 2.2.

3.2 *Control of the Manufacturing Process*

Most of the semiconductor devices were obtained as early as possible in order to provide a suitable time period for certification life testing. They were therefore taken from product already manufactured under normal quality control and inspection techniques. A sample of each lot of product obtained, however, was subjected to step-stress testing where applicable to assure that the failure pattern would match that expected from the design qualification tests or from previous experience. Some of the diffused germanium high-frequency transistors, however, and three types of special diffused silicon diodes were manufactured specifically for the Telstar program and were made under direct engineering control with careful scrutiny of each step of the processing.

3.3 *Screening and Pre-Aging*

Table V shows the list of the various screening and pre-aging conditions used to eliminate early failures from the product. Each condition was considered for at least one of three reasons: (1) general applicability

TABLE V — SCREENING CONDITIONS

Mechanical
Centrifuge
Temperature-humidity cycle
Tap, shock or vibration
X-ray inspection
Temperature cycle
Reliability
High-temperature processing

of the testing condition for quality control, (2) knowledge of the design which would cause concern about capability of every individual device to withstand the environmental condition or (3) specific requirements of the application. In addition, when prior experience was not available, tests were made to obtain assurance that the environmental screening condition would not induce additional incipient failures into the product and would, in fact, eliminate devices which were distinctly weaker than the normal population. Not all conditions were used for each type, and the choice of conditions for each type was determined, at least in part, by results of the qualification tests.

Results of the mechanical screening operations are presented in Table VI. The low rejection rate of the diffused germanium high-frequency transistors, in comparison to that of the silicon transistors having a generally similar structure, is felt to represent the improvement due to the careful attention given them during fabrication. On the other hand, the high rejection rate of the alloyed germanium types for power use reflects marginal capability of meeting screening conditions for which these particular types were not originally intended.

Reliability screening, or pre-aging by the application of high temperatures, was used only in one case where the qualification testing indicated early failure rates could be improved. In most cases such proc-

TABLE VI — MECHANICAL SCREENING RESULTS

	Number Processed	Per Cent Rejects
Diodes		
Microwave	774	2.3
Rectifier	3,292	3.0
Small Signal	24,109	0.27
Transistors		
Power (Ge)	635	9.5
High Frequency (Ge)	4,780	0.3
Amplifiers (Si)	24,229	2.8

essing was included in the normal production sequence and was not repeated in this program.

In addition to these results of the planned program, additional mechanical screening was required later for two diode types when molded into a module. The molding flash removal operation was apparently causing damaging shocks to be transmitted down the diode leads. Although alteration of the flash-removal process appeared to eliminate the problem, diodes were also given a very severe tap test which caused rejection of 25 per cent of the diodes for that application.

Subsequent to the initial radiation evaluation it was recognized that devices held under electrical bias while being exposed to ionizing radiation could suffer degradation at a much lower dose than that necessary to produce permanent damage in the semiconductor material.[6] This effect occurs in quite varying degrees in transistors of different types and among individuals of a sensitive type. It apparently results from ionization of the gas ambient in the device and the effect of such ionization on the semiconductor surface. All types were therefore exposed to ionizing gamma radiation from a Co^{60} source for short periods at an accelerated dose rate of about 10^6 rads per hour and for long periods at a dose rate of 5 rads per hour, simulating the exposure expected in the Telstar satellite orbit, according to data available prior to launch. Those types showing no degradation under either exposure were considered qualified for this environment. Those types showing degradation were given additional radiation screening, consisting of exposure while under bias in normal transistor operation, for one minute in a γ-ray dose of 8.5×10^5 rads per hour. This provided a total dose of 1.4×10^4 rads, the equivalent in ionization energy to that dose expected in three months in the satellite orbit for devices shielded in the electronics canister. Such screening was necessary for two types of silicon mesa transistors. Fig. 1 shows an example of the distribution (on a normal probability scale) of the increase in collector reverse current (I_{CBO}) of one of the transistor codes after screening, indicating the percentage selectable at any stated screening limit for three months in orbit. (The measurements prior to radiation were in the 10^{-10} to low 10^{-9} ampere range.) Since for these types the I_{CBO} increases beyond this value approximately as the $\frac{1}{2}$ power of total dose, a selection for two-year operation (eight times the equivalent of the screening dose) is made by setting the I_{CBO} limit for screening a factor of 2.8 tighter than the circuit limit. Some additional safety factor is desirable because of the lack of perfect correlation between screening dose and dose in orbit. The knowledge of this response to radiation and the distribution thereof allows careful matching of screening limits and circuit use requirements, if necessary to obtain maximum screening yield.

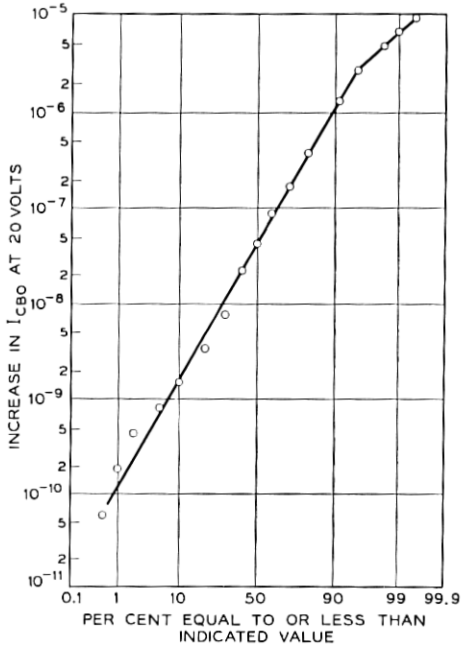

Fig. 1 — Distribution of reverse current degradation resulting from radiation screening.

Suitable selection was made of these types, without allowing more than two orders of magnitude increase for use in the most lenient circuit.

Subsequent low-level exposure tests[6] have confirmed the effectiveness of this screening procedure through equivalence of its results to those expected in orbit. Fig. 2 shows the distribution, on a normal probability scale, of the ratio of h_{FE} of one of the transistors after the screening dose to that before screening. This shows that, in the total population screened, 10 per cent suffered degradation to below 30 per cent of the original measurement. Since increases in gain were not of concern, the screening selection affected most strongly the units degrading most. The units with highest initial gain suffered the greatest percentage of degradation in screening, while those with lower initial gains degraded less or tended to increase, so that the problem of selecting units with sufficiently high gain after radiation was not severe.

3.4 *Selection of the Most Stable Components*

In order to select the best devices from the available product, all devices were subjected to a life testing period of an intended six-month duration or for as long as possible between the time of availability and the deadline for shipment. (For the devices selected for the Telstar satellite, the average life test was about fifteen weeks.) During this life test period all pertinent parameters were measured on each device at regular intervals, generally of the order of two weeks. Up-to-date listings were kept of the data on each device so that the life history could be examined readily for drifts of characteristics, unusual variations in measurements, proximity to critical circuit limits or the existence of wild and unexplainable readings.

All the devices were operated at electrical conditions close to those at which they would be used in the satellite or close to the most severe condition for those types used in several circuit applications. On this basis, the operating condition was typically in the order of 10 per cent of the normal device rating. Although this does not take advantage of the acceleration of changes which might be induced by higher power levels, it was considered to be the safest approach. Furthermore, this resulted in some of the transistor types operating at quite low currents, at which the gain measurements are more sensitive to changes, and differences in stability between individuals may have tended to show up even more readily than at the higher power levels. Most of the devices were installed in modules which could be inserted into the aging equipment or into the test equipment without additional handling of the device itself.

The selection process consisted of obtaining the most stable units on the basis of the recorded life data and electrical measurements before

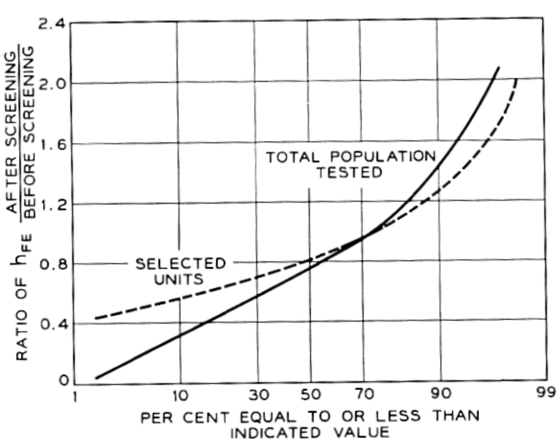

Fig. 2 — Distributions of h_{FE} degradation, of total group screened and of selected units, resulting from radiation screening.

and after the various screening procedures. Whereas many of the lots were sufficiently small that this could be done readily by observation of the data listings, other lots were sufficiently large that the initial selection was done by machine as much as possible. A computer was programmed to estimate the time at which each device would exceed an established limit for any parameter, considering drift, variations, and the initial values. The individuals were then ranked according to these time estimates and a listing was prepared from which selections could readily be made.

The final certification of each device chosen for use consisted of a complete review of all electrical measurements, X-ray photographs and similar data by qualified technical personnel, stamping of the proper code number to identify the circuit application intended and final inspection and electrical test. Many of the general considerations were similar to those described for passive components in Section 2.3.

3.5 *Evaluation of Life Testing and Selection*

It is of interest to review the life testing data and the results of selection, in order to observe the effectiveness and the degree of discrimination of selection and to obtain some estimate, if possible, of the probable reliability of the selected units.

Fig. 3 shows one example of the selection sensitivity for one parameter of a silicon mesa transistor. This plot, on a normal probability scale, shows the distribution of the rate of change of h_{FE}, or transistor current gain, in per cent change per month, averaged over the life test period (six months in this case). Silicon transistors typically experience a slight increase in gain early in life, becoming quite stable thereafter, and the total population on this life test shows, for most of the units, this typical increase. About 4 per cent of the total, however, evidence a negative drift, indicating degradation of the order of 1 to 2 per cent per month or more, this portion of the product also deviating from the Gaussian distribution indicated by the straight line of the rest of the product. The distribution of the selected units shows the complete elimination of the degrading units. Those having the expected increase in gain during life test have stabilized during the latter part of the test and are stable at the time of selection. It is felt important that the life testing period be sufficient to provide the data necessary to distinguish such a distribution and such a deviation from it.

Another means of evaluating life test results consists of assigning "defect" limits to the electrical parameters being measured for each

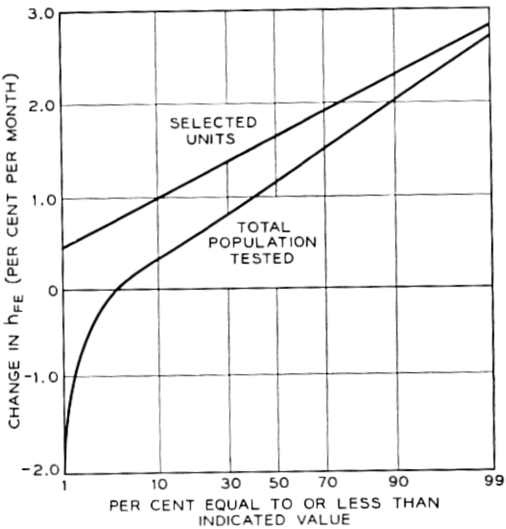

Fig. 3 — Distribution of h_{FE} degradation rate on life test, for total group life tested and for selected units.

transistor or diode type and noting the frequency of occurrence of units exceeding these limits. Such limits were defined for the major types on life test, and Fig. 4 shows the resulting plot of defect rates for a typical transistor and a typical diode. The defect rate, in defects per 10^9 component hours, is calculated for life test intervals and is plotted with time on test, on a log scale, showing the decreasing "failure" rate typically reported for semiconductor life tests. The shape and general position of the curves are also typical of most of the types on life test and show the marked gain which can be achieved in defect rate of the product through such a life test period.

It is also noted that the defect rate of about 1000 defects per 10^9 component hours for transistors, or 100 for diodes, at the selection time of about fifteen weeks is appreciably above the 10 failure units set as the maximum objective for Telstar satellite semiconductors. In order to estimate probable failure rate of Telstar components from the life test data, however, certain factors must be considered. A large factor is that the spacecraft components are selected as the most stable ones, whereas the life defects represent generally the least stable. Most of the defects occur by degradation of a measured parameter to the defect limit, this degradation being recognizable early in life. The certified units are those with no definite degrading trend and hence should not be subject to such failures. The only indication of possible failures from among the selected units is the frequency of catastrophic life test defects, a measurable rate much below that of the total defect rate. Additionally, since most of such sudden changes occur in units showing some tendencies which would otherwise prevent their selection, the measurable estimate of improvement from total defect rate to estimated catastrophic failure rate of the selected units is considered quite conservative.

Many of the device types are used in several circuits, some of which have requirements for device parameter limits which are relatively severe compared to the majority of circuits using that type. The life defect limits correspond to the most severe requirements, and the calculated defect rate is therefore much greater than that which would be representative of the major portion of that product. The average failure rate is therefore additionally reduced by as much as a factor of ten for some types for this reason. The frequent testing is another factor which may have more bearing on some types than on others, but may always be present. Consideration of all these factors for each type, to the degree measurable, indicates conservative ratios of from 10 to 200 between life defect rates and estimated circuit failure rates.

Table VII shows a summary of the defect rates by device classes taken from such plots as in Fig. 4 for the time of shipment of Models 1 and 2 of the satellite and of Models 3 and 4. These data include over 90 per cent of the types, excepting those for which the numbers on life test were too small to develop meaningful statistics — among these being the germanium alloy types for power control use. Among all types, the lower defect rate for the second shipment time shows the effect of the decreas-

Table VII — Life Test and Selection Results

	Number per Satellite	Defect Rate at Shipment Time, Defects per 10^9 Component Hours		Conservative Failure Rate in Satellite, Failures per 10^9 Component Hours	
		Models 1 & 2	Models 3 & 4	Models 1 & 2	Models 3 & 4
Diodes					
Microwave	14	4,500	3,000	45	30
Rectifier	83	30	20	3	2
Small signal	1,424	70	35	3.5	2
Transistors					
High frequency (Ge)	94	550	400	13	10
Amplifiers (Si)	1,011	4,000	3,000	30	20
Weighted average				14.2	9.3

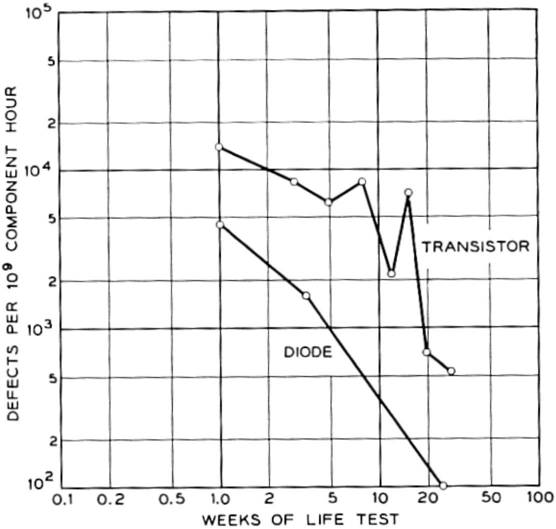

Fig. 4 — Defect rates through life test for typical transistor and diode.

ing defect rate as shown in Fig. 4. The relatively high defect rate of the silicon transistors for general amplifier use comes about largely through the contribution of one type which had a defect limit on collector reverse current, I_{CBO}, of 10^{-8} ampere, a much lower figure than that normally used for life test limits. Also shown for each class of product are the failure rate estimates for the selected devices, taking into account the factors mentioned above.

With these failure rate estimates weighted according to the number of each class of device used per satellite, an over-all average can be calculated, indicating about 14 failure units for the Telstar satellite semiconductors, with an expected improvement to 9 failure units for Models 3 and 4. Since these estimates are conservative, as indicated above, it is felt with considerable confidence that the screening and life testing program has resulted in devices meeting the initial objective of less than 10 failure units.

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