he Lenkurt® Demodulator

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New knowledge about
TRANSISTOR RELIABILITY

The transistor, born of telephone research, has been long-delayed in appearing in telephone and other multi-channel communications equipment. Despite the difficulties of supplying power across an ocean, designers of the long underseas cables turned to electron tubes in order to assure themselves that the built-in repeater amplifiers would continue to operate over a twenty-year period. Why has the transistor, once hailed as the final answer to tube failure problems, been so conspicuously absent, until now, from most communications equipment? This article discusses some of the causes of transistor failure and the techniques that are restoring hope that the transistor may soon be the most reliable of all electronic components.

An urgent United States missile development program has focused new attention on the problem of component reliability. The "Minuteman" missile, dedicated to providing incentive for continued world peace, is designed to rest unattended in buried launching tubes in widely-dispersed locations. Missiles are so extremely complicated and have so many interdependent systems that satisfactory operation in the absence of constant care and maintenance requires a level of reliability that is incredible by conventional standards.

The significance of this missile program to the communications industry lies in the radical new approach to designing a reliable system in a field which is notorious for its vulnerability to the failure of individual components. Actually, there is a remarkable similarity between the reliability requirements of

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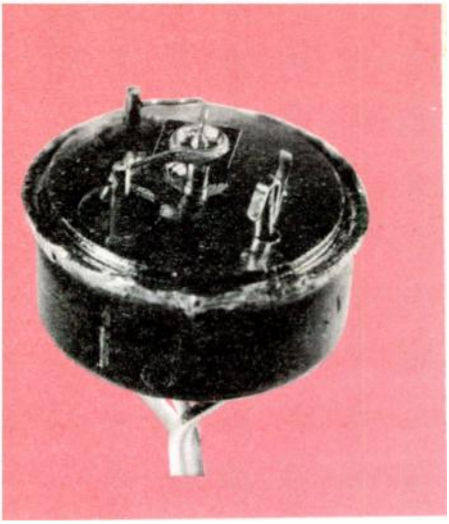

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Figure 1. Typical junction transistor (from which upper case has been removed), shown here greatly enlarged. The square plate is only about 1/50 inch (½ mm.) on each side; the junctions which comprise the central spot and the ring are extremely small.

missiles such as "Minuteman" and large communications systems. Both are extremely complex, thus requiring close control of the performance of individual parts; both are important, since large-scale failure of either would have dire effects on general well-being. In both, it is vital to have a realistic appreciation of system dependability so that enough standby equipment can be provided to guarantee the required service. Obviously, the more reliable the system, the better the performance that can be provided at a reasonable cost.

In order to assure the astonishingly high degree of reliability required for the success of the "Minuteman" project, intensive reliability programs have been established in all the industries which supply parts for the missile. One of the most important of these programs is centered in the electronics industry, since the success of a solid-fueled missile is more dependent on electronics than almost any other single factor. As a result of this and other urgent research programs, all users of transistors benefit from the improved devices which result.

Status of Transistors

Compared to electron tubes, transistors are still a very new type of component. In the past few years, diligent research has rapidly broadened the range of applications for which transistors are suited. Transistor frequency response and power handling capability have been increased greatly, while noise generated within the device has been steadily reduced. Inherent difficulties in using transistors for certain applications are rapidly being overcome by the development of new circuit techniques (see DEMODULATOR, *September* and *October*, 1961). Of all the benefits expected of transistors, only reliability has lagged behind its potential.

This estimate of transistor reliability is relative, of course. Despite the immaturity of transistor technology compared to electron tube techniques, many types of transistors are about ten times as reliable as most tubes, and are on a par with wire-wound resistors and foil capacitors (assuming, of course, that the transistors are properly used).

Progress is quite rapid in improving transistor reliability. Only about two years ago, several studies showed that electron tubes and transistors showed about the same rate of failure in military equipment. Although progress in increasing transistor reliability is excellent, there is plenty of opportunity for improvement, since the basic transistor action does not wear out, and is basically impervious to shock.

When quality control engineers speak of reliability, they refer to the *probability* that a device will continue to function within certain design limits for a given period of time. It is usually expressed as % failures per 1000 hours of service or as the Mean Time Between Failures (MTBF). In some applications such as pocket radios, performance limits may be very broad, thus allowing lower grade units to be used. In military and communications equipment, however, requirements are usually much more stringent in order to maintain suitable performance reserves. Transistors are considered to have failed once their performance characteristics drift beyond a certain specified limit. Some typical estimates of electronic component reliability are given in Table 1.

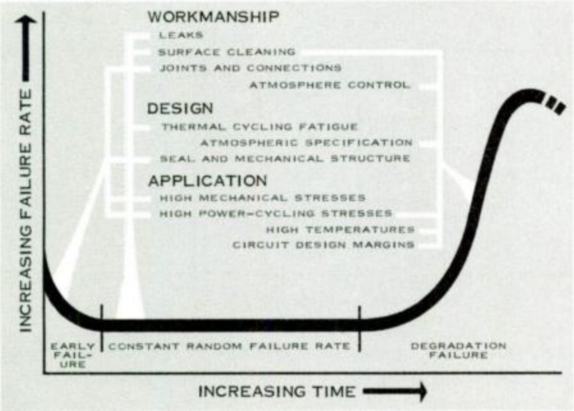
Table 1.
Typical Failure Rates

Component	*Present %/1000 hr*	*Minuteman Objective %/1000 hr*
Transistors		
Computer	0.07	0.0007
General	0.1	0.001
Power	0.4	0.004
Diodes		
Computer	0.02	0.0002
Other	0.1	0.001
Capacitors		
Solid	0.5	0.001
Foil	0.1	0.001
Glass	0.05	0.0006
Paper	0.001	0.0006
Resistors		
Carbon Composition	0.001	0.0001
Metal film & grid	0.04	0.0004
Wire Wound	0.1	0.001

COURTESY OF ELECTRONIC INDUSTRIES

Why Transistors Fail

The successful manufacture of transistors requires rather incredible precision and control at every step in the process. The basic quality of transistor action depends on the precision with which specific impurities or "dopants" are added to the silicon or germanium in making the *p* and *n* layers which form the transistor junctions. The basic raw material must be so pure that impurities are measured in parts-per-billion. If



GENERAL ELECTRIC SEMICONDUCTOR PROD.

Figure 2. Generalized transistor failure rate pattern, with major influencing factors. Most sources of transistor failure are now being controlled by using automatic machinery almost exclusively for fabricating the devices.

these requirements are not adhered to scrupulously, performance may be badly degraded or even unattainable.

Transistors are remarkably small devices, sometimes consisting of a tiny slab of base material less than 0.02 inch on a side, and onto which are bonded or deposited tiny spots of material which become the collector and emitter. These tiny junctions, which are sometimes smaller in diameter than a human hair, are the gates through which the signal must pass and which must be capable of handling the full range of signal power. Figure 1 shows a typical transistor with the case removed.

Transistor failures are usually broken down into two basic categories: *catastrophic* failures and *degradation* failures. Catastrophic failures are those in which the device completely stops functioning, often the first time it is used or tested. Most failures of this type are caused by mechanical defects such as open circuits, short circuits, improper bonding of leads, and the like. Usually this type of defect is relatively easy to discover by inspection during assembly. A smaller number of catastrophic failures occur a little later in the life of the transistor from such causes as thermal cycling which may release contaminating material from the case, loosen improperly soldered joints, or volatilize a contaminant so that it is deposited on the junction. Many manufacturers now subject all new transistors to short, severe trial runs which are designed to eliminate the "weaklings" at the very outset.

Much more insidious are the degradation failures, since they may not appear for many thousands of hours and may even then only consist of degraded performance, rather than absolute failure. Surprisingly, the performance characteristics of almost all transistors tend to degrade with time, whether in service or not. In fact, because of the thermal gradient at the junction, some transistors appear to maintain more stable characteristics in service than during storage. Figure 2 summarizes the causes for most transistor failures.

Two basic performance characteristics are usually chosen as indicators of tran-

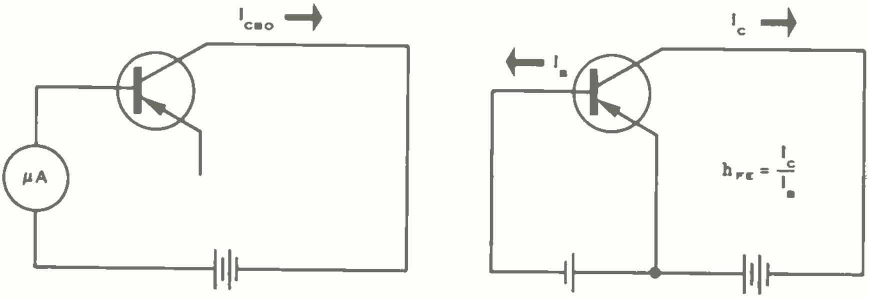


Figure 3. Typical method of measuring transistor parameters. Collector leakage current (I_{CBO}) is measured with reverse-bias, as shown in sketch at left. Direct current gain (h_{FE}) is ratio of output current to input current in common-emitter circuit.

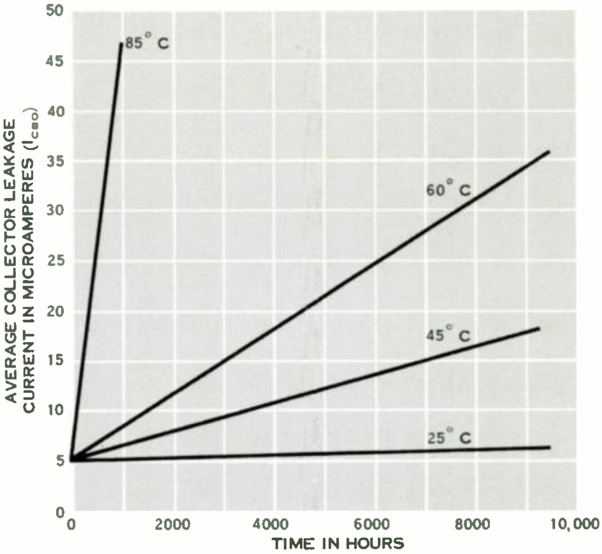


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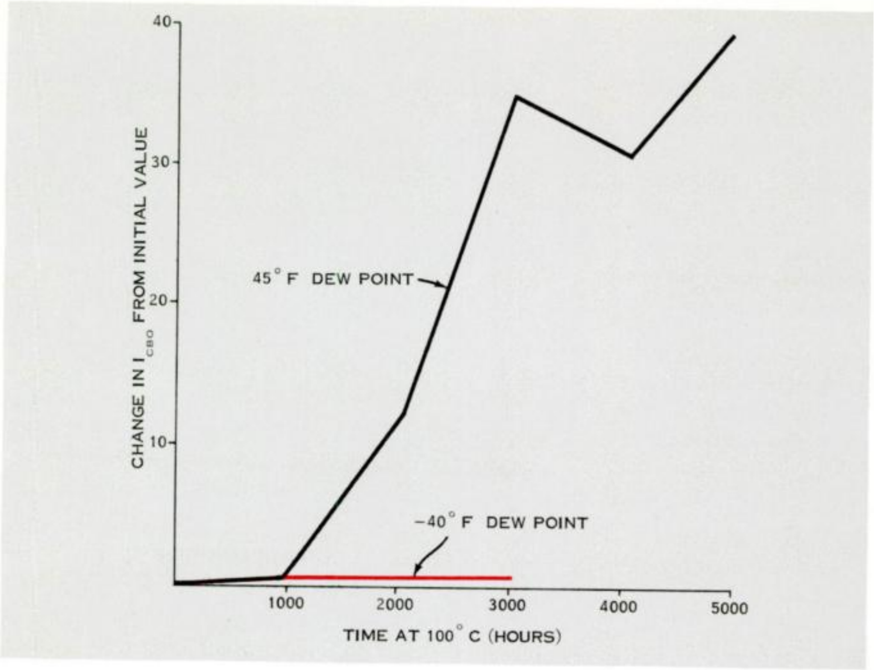
Figure 4. Effect of storage temperature on performance degradation of an experimental germanium transistor. Even at 25° storage temperature, some drift in performance is experienced.

sistor performance stability because they are the parameters most likely to change with time: one is the leakage current from collector to base when the collector is reverse-biased and the emitter is left unconnected; this leakage current is usually designated I_{CBO}. The other is the d-c current gain in the common emitter arrangement, with the emitter grounded. This is usually designated h_{FE}, and is the ratio of collector (output) current to base (input) current. These basic relationships are diagrammed in Figure 3. A low value of I_{CBO} leakage current is desirable, but in most transistors tends to increase with time, particularly when the device is stored or operated at elevated temperatures, as indicated in Figure 4. Increased leakage current is often accompanied by a corresponding reduction in h_{FE} and generally poorer performance. When these characteristics finally exceed the specification limits on which circuit designs are based, the transistor is considered to have failed, even though it may still function to some degree.

Contamination

Transistor degradation appears to result from three basic factors: the presence of fantastically tiny amounts of foreign substances or contaminants within the transistor case, moisture, and elevated temperatures. Apparently, all three work together, altering the nature of the transistor material and creating leakage paths across its surface. Since the action is progressive and becomes greater with higher temperatures and longer periods of time, it seems likely that the moisture helps ionize the contaminating substance so that it can enter into a chemical reaction with the transistor material, thus changing its nature. Some transistor degradation by moisture is reversible, however, as evidenced by the fact that intermittent operation of the transistor, or continued operation of the transistor at low power may result in



SYLVANIA ELECTRIC PRODUCTS

Figure 5. The effect of moisture in transistor case on leakage current. Transistors manufactured in dry-box (dewpoint = −40°F) showed I_{CBO} drift indicated by red line. Black line indicates degradation experienced by identical transistors assembled and sealed in moist air (dewpoint = 45°F). Both groups included moisture-absorbing dessicants.

less degradation than would occur on the shelf. Evidently, the heat generated at the transistor junction tends to drive the moisture away from the junction. However, if the transistor becomes sufficiently hot, the increased operating temperature accelerates any degrading chemical action.

Contamination of the transistor material is a very serious problem, and manufacturers go to remarkable lengths to eliminate it. Purity of materials is maintained at an extremely high level. Water used for cleaning during the manufacture of the transistor is, for instance, normally deionized so completely that it has a resistivity of 16 to 18 megohms per centimeter. Almost all manufacturing operations are conducted in so-called "white rooms" in which dust, air purity, and humidity are very closely controlled.

Moisture

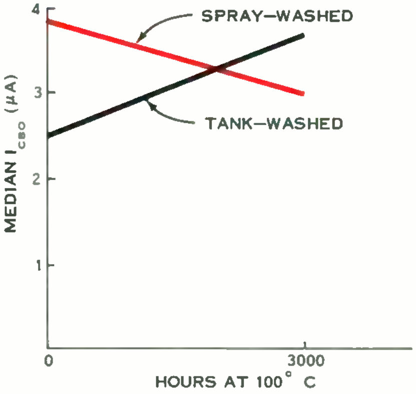
Probably the most important single factor in the reliability of transistors (other than how it is used) is the amount of moisture remaining in the case after it is sealed. One way of restricting the amount of moisture and contaminating substances that reach the transistor junction is to include encapsulating materials in the transistor case. These may be desiccants for taking up moisture, "getters", or molecular sieves which trap contaminating molecules of many types. Both liquid and solid types are used, frequently in combination with each other. Even these devices vary considerably in their effectiveness, according to how carefully they are prepared. It should be noted, however, that oil alone is a "barrier" material and may only delay the onset of degradation. This may actually impair reliability by giving false indication of actual quality as indicated by measurement of I_{CBO}.

Figure 5 gives the results of a test designed to show the effect of tiny amounts of moisture left within the case. The transistors represented by the black curve were encapsulated and sealed in a room in which the dewpoint was 45° F. A similar group of transistors (red curve) was encapsulated and sealed in an extremely dry atmosphere in which the dewpoint was −40° F. Identical desiccants were used in both. Since handling and processing were identical in every respect for both groups, the rather dramatic increase in I_{CBO} for the group processed in the moist room can only be accounted for by the effect of the moisture that the desiccant was unable to take up.

Although the moisture often has a direct effect on transistor degradation, it more likely serves as a vehicle for other contaminating substances, creating ions which enter into chemical reaction with the junction material. The cleaner the transistor material, the case, and the leads, the less likelihood there is that the finished transistor will exhibit severe degradation.

The remarkable sensitivity of transistors to efficient cleaning was demonstrated in another test in which one group of transistors was washed in a single tank of turbulent, ultra-pure water for one hour, and another group was tank-washed for twenty minutes and then spray-washed for five minutes. After three thousand hours storage at 100° C, the spray-washed transistors showed a reduction in I_{CBO} leakage current, while the I_{CBO} of the tank-washed devices increased after storage at 100° C, as shown in Figure 6.

Another experimental technique which was effective in delaying the onset of degradation was to add special substances to an etching bath used in the transistor manufacture, so that the contaminating substances were "snapped up" to form complex ions which had less contaminating effect. Eventually, transistor degradation reached approxi-



SYLVANIA ELECTRIC PRODUCTS

Figure 6. Even using purest water, minor differences in washing technique have important effect on ultimate performance of transistors. Spray-washed transistors were adjudged to have better stability.

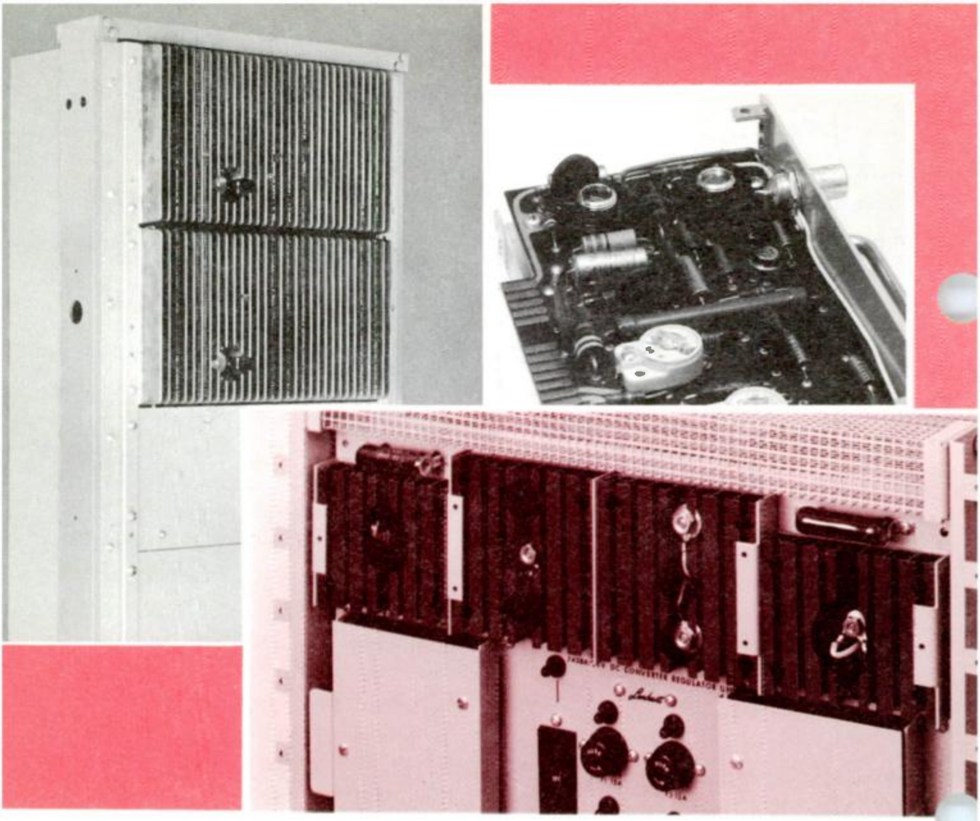


Figure 7. Upper left illustration shows massive finned heat sink used to dissipate heat from transmit klystron in transistorized 76A microwave transmitters. Radiating fins are attached to power amplifier transistors in 76A modulating amplifier (upper right). Note low-level transistor without special cooling. Special cooling fins are used for power transistors used in transistorized power regulator, shown in lower illustration.

mately the same value as in transistors made without the complexing substance, although the onset of degradation was delayed several thousand hours. This suggests that the complex ions thus formed were either unstable, or that they were slower in entering the junction area.

By using these and related techniques, transistor manufacturers have been able to produce devices which may be stored 30,000 to 100,000 hours at 100° C before the onset of performance degradation.

Reliable Equipment

Once the transistor has been sealed and shipped, the life expectancy and performance of the device is in the hands of the equipment manufacturer. Although extreme measures are taken to make each transistor as nearly perfect as possible, there is a great likelihood that this objective will not quite be reached. Accordingly, transistor performance will tend to degrade with time.

Transistor degradation will be accelerated or delayed by the manner in which the devices are used, since degradation becomes a function of the transistor junction temperature. In general, transistor life is reduced by about half for every ten-degree increase in junction temperature. The more power handled by the transistor, the greater the temperature, and the shorter the potential life of the device. Although the transistor may not generate many calories, the junction area is usually so minute that even a small amount of heat will result in a rather large temperature rise at the junction.

Equipment designers have a number of techniques at their disposal for dissipating the heat generated by transistors. First, of course, is to limit the power handled by each transistor by designing circuits conservatively. Another important technique is to design the equipment to provide natural routes for the heat to escape from the transistor. Such means include radiating fins on the transistor, mounting the transistor on some sort of heat sink that conducts the heat away, or which increases the surface area from which the heat may radiate. In addition, transistor equipment should be designed to isolate sources of heat from the transistors themselves, in order to permit the most rapid transfer of heat away from the junction as possible.

Figure 7 illustrates several ways of dissipating heat so that transistors will operate at a lower temperature. By using fins with large areas, heat is rapidly transferred to the surrounding air. The temperature of the surrounding air thus controls the junction temperature, since the transfer of heat is directly proportional to the difference between the temperatures of the transistor junction and the air. The larger the radiating surface, the more nearly the junction can approach the temperature of the outside air.

By employing such techniques judiciously, engineers are now producing equipment which takes full advantage of the tremendous longevity available from modern transistors. Future equipment will carry this trend further, perhaps even using such techniques as thermo-electric cooling devices within the transistors themselves! •

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