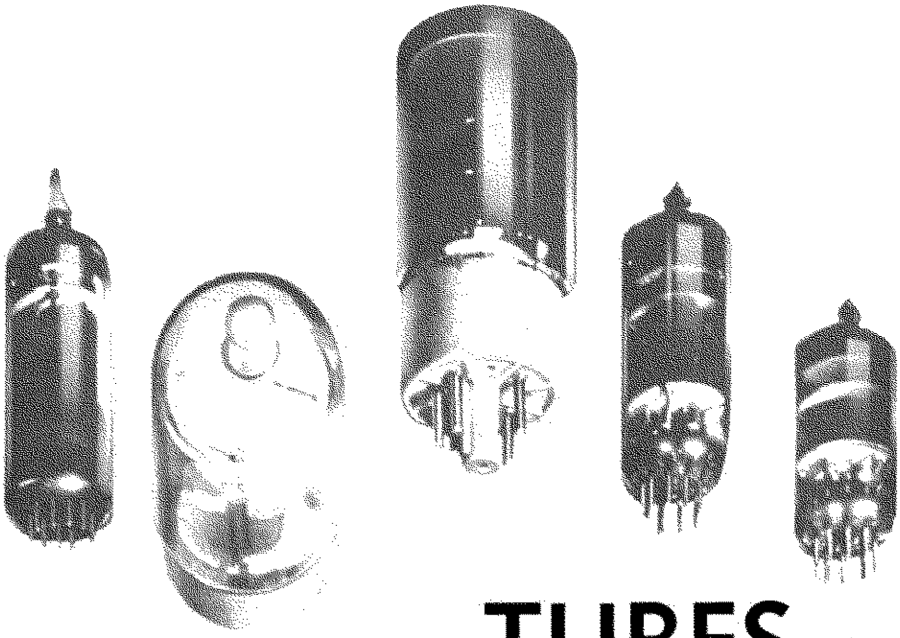

TUBES or

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THE popular notion that transistors will undoubtedly replace vacuum tubes in the near future has received a lot of publicity, due in part to the natural enthusiasm and optimism of the many new firms designing and manufacturing semiconductor devices. There is, of course, no doubt that transistors will take over some of the application areas previously served by tubes, and that there will be some grey areas where either tubes or transistors will serve equally well, but the fact is that there are many, many fields where tubes are, and will continue to be, superior.

R. E. Moe

The advantages and disadvantages of each device, under the wide variety of operating conditions and circuit requirements, should govern the choice for a particular application, and the following discussion is intended to bring out those which are pertinent to such an analysis.

The purpose of this discussion is to present briefly a few extracts from the available data, and list references giving more complete information, to allow a realistic assessment of performance and reliability factors of interest to the designer of electronic equipment.

Broadly speaking, electronic equipment breaks down into two groups—entertainment, including radio and TV, on the one hand, and industrial and military on the other. The first may be disposed of at this time by the statement that cost will continue to be the governing factor dictating the use of tubes, except in the personal portable field, and the output stages of car radios.

In the industrial and military fields where cost is less of a factor, the relative performance and reliability factors must be examined more critically.

The following points have been chosen as prime factors that should guide the designer's choice, depending of course on his equipment specification requirements:

1. Power input (efficiency).
2. Ambient or hot spot temperature.
3. Upper frequency limit.
4. Noise figure.
5. High voltage requirement.
6. High power output requirement.
7. Spread of characteristics and tolerances.
8. Combination and multiple units.
9. Nuclear radiation.
10. Reliability.
11. Physical size and weight.

Let us see how tubes and transistors compare on each of these counts.

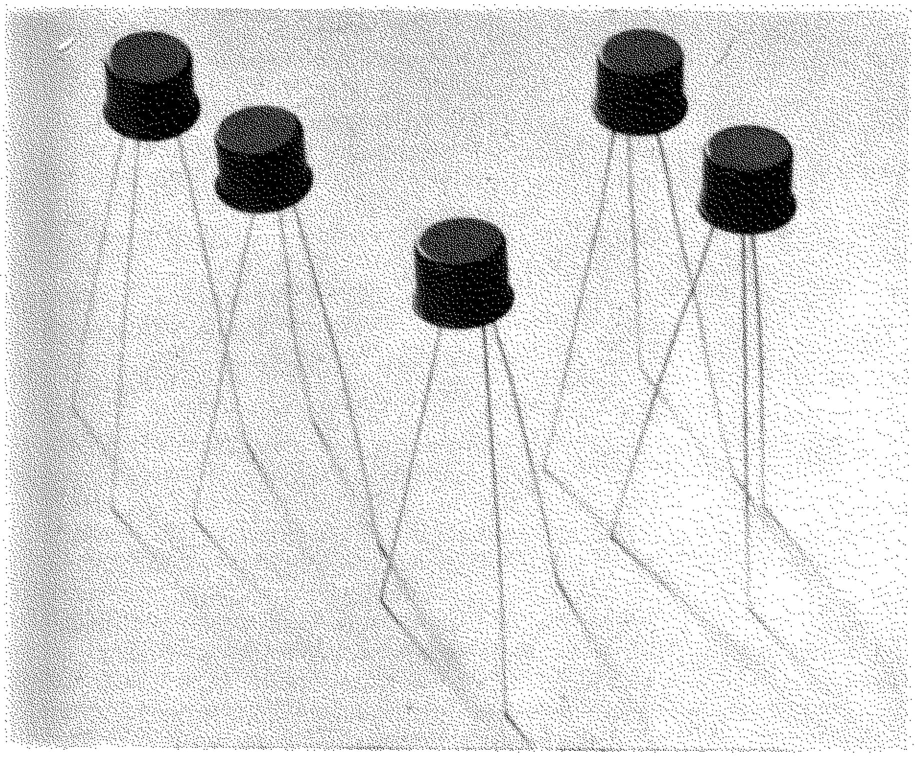
Power Requirements

If available power input is limited, and high power output is not a prime requirement, transistors

Ed: It has become commonplace in the trade to hear reports of over-transistorization — transistors being used where their inherent weaknesses put them at a disadvantage. This has been particularly true in military gear where the practice is doubly serious because the price is paid in terms of reliability. We do not pretend to know where the fault lies. It is enough to say that these mistakes are being made. We hope that this article will provide a fresh basis on which design engineers and those specifying electronic equipment can intelligently answer for themselves the question—tubes or transistors?

The development of transistors has now reached a stage where we can say that certain inherent obstacles to further development exist. Frequency range, ambient temperature, high-voltage applications, nuclear radiation—these requirements will limit transistor use well into the foreseeable future. It is time to spell out just where transistors can be expected to do the job best and where tubes should be used.

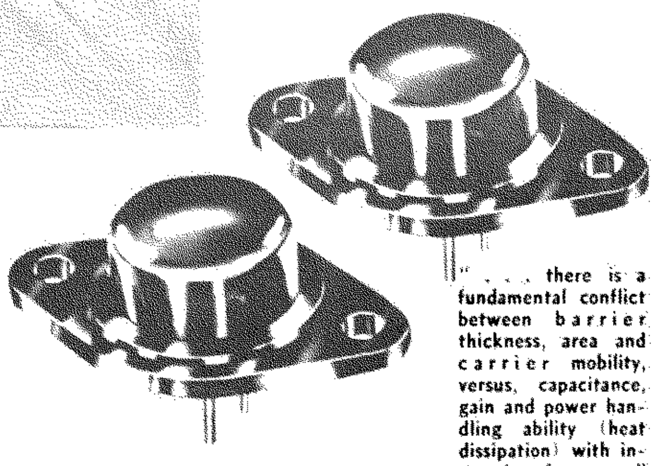
TRANSISTORS?



are the logical choice. For example, in hearing aids, personal portable radios, or even space satellites, which are supplied by battery power, the low drain and high efficiency of these devices are the prime factors. On the other hand, if the equipment is to be AC operated, these factors are of little consequence, and other considerations may well favor tubes over transistors. For example, fixed station receivers and transmitters, or multiple PA systems, should be simpler and more economical using tubes.

Ambient Temperature

Owing to the inherent nature of semiconductors, their characteristics are far more sensitive to changes in temperature than are tubes, so that germanium and to a lesser extent silicon units show considerable variation in parameters with changes in temperature, and reach a limiting capability around 100°C and 200°C junction temperature, respectively. Tubes, on the other hand, can operate well above 200°C bulb temperature in the glass types, and over 400°C in ceramic, with practically no change in characteristics. Thus the use of transistors under varying ambient conditions requires a great deal of attention to temperature compensation elements and feed-back circuits, where in most cases these precautions are unnecessary when using tubes. (For the 2N176, I_{co} is specified at a maximum of 3.0 ma at 25°C and 30 volts, and a maximum of 15.0 ma at 90°C junction temperature and 30 volts.) In fact, the serious degradation in performance of transistors with increasing temperature may well make their use uneconomical because of the low gain per stage, or limited output available at the high end of the operating temperature range, well before the advertised temperature limit is reached.



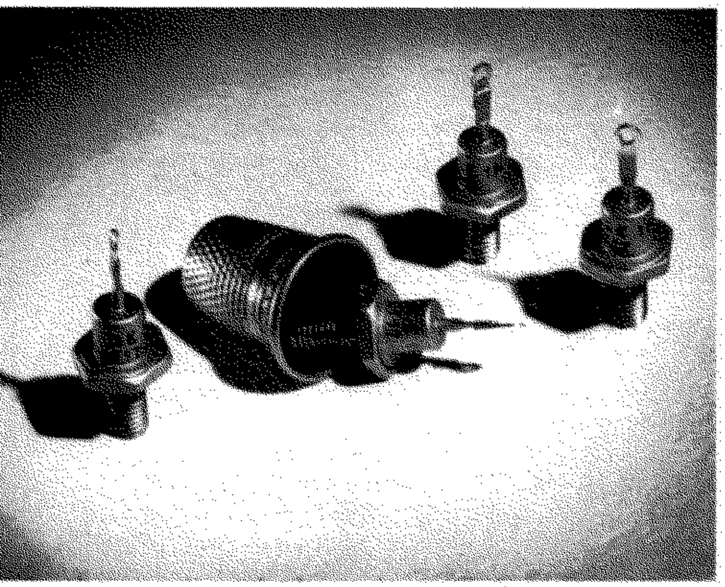
". . . there is a fundamental conflict between barrier thickness, area and carrier mobility, versus, capacitance, gain and power handling ability (heat dissipation) with increasing frequency."

Tubes or Transistors

(Concluded)

There is also the need for precautionary measures when soldering transistor leads, to prevent overheating the junction and damaging it permanently.

To quote Captain W. I. Bull: [2] "Presently the temperature requirements for components range from —65° to +200°C. Guided missile and Mach 2-plus manned aircraft may require components capable of providing reliable operation in ambients of 250° to over 500°C. The goal for the development of an entire line of high temperature, 500°C component parts, is 1965. In view of the temperature limitations of germanium and silicon transistors, new semiconductor materials will have to be investigated (and this means "developed, perfected, and reduced to practical manufacture."—ed.), and device development programs must be initiated on the most promising materials if the military's high-temperature part objective is to be met.



"Because of the inherently better insulation afforded by vacuum devices it is expected that tubes will be more reliable for high-voltage applications for some time to come."

Frequency

With presently available constructions and techniques, transistors become increasingly difficult and expensive to build for operation above 500 KC. Refinements, of course, are being introduced, but there is a fundamental conflict between barrier thickness, area, and carrier mobility, versus capacitance, gain and power handling ability (heat dissipation) with increasing frequency. Tubes, of course, have this to some extent owing to transit-time effects and interelectrode capacitance loading, but to a much smaller extent. Even the most optimistic predictions by transistor manufacturers provide little hope that they will take over present VHF and UHF tube applications (from 100 to 1,000 MC) in the foreseeable future, unless other considerations than cost and gain govern the choice. As an example, some mobile communications equipment are now being transistorized. There are very few transistor types registered for this kind of operation, and none with approved military specs.

Also, several set manufacturers have produced experimental samples of transistorized portable TV receivers, but they will admit that it was necessary to exercise a great deal of selection to find the right kind of transistor to perform several of the more critical functions, and that would certainly not be practical at this time.

Noise

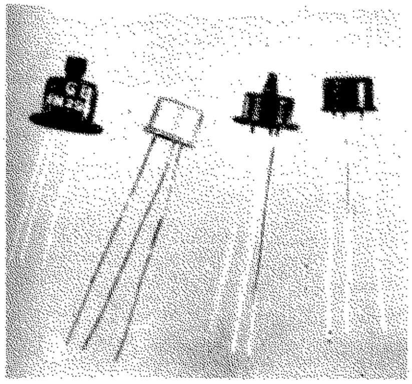
Although relatively free of microphonics and variable leakage path noise contributions, transistors have an inherently higher random noise output than tubes, when considered on a noise power basis ($KT\Delta f$). Thus transistors may well be chosen for low level stages of audio pre-amplifiers to eliminate microphonics and hum, but be unsuitable for wideband IF or RF amplifiers in radar or television, where a noise figure approaching the theoretical minimum is a prime requirement. The ceramic 7077 is quite a bit better than the best transistor for ultra-low frequency flicker noise.

High Voltage

Because of the inherently better insulation afforded by vacuum devices, it is expected that tubes for high-voltage applications, both diodes and multi-element, will be simpler, more economical and more reliable than semiconductors for some time to come. Such things as high-voltage sweep tubes, rectifiers, and dampers for supplying 20 kv to television picture tubes or radar indicator scopes will be difficult to displace, unless some more efficient methods are found which can tolerate the lower breakdown voltage limitations of semiconductors.

Another aspect of this same weakness is the inability of transistors to withstand power supply transients as experienced in aircraft generator systems, which have been found to vary between —25 and +80 volts on a 28-volt DC system,[3] or diode breakdown when using a continuity meter to check out a circuit, inadvertently applying excess reverse voltage to the semiconducting element. In fact, the elaborate protective devices necessary in the former case make such applications of dubious value.

To quote a Collins Radio author,[3] "In summary, it can be said that transistors and other semiconductor devices can be successfully used in environments exhibiting the hazard of extreme positive and negative voltage transients *if* proper design techniques are used. It must be recognized that protection of equipment from transients, especially that using power transistors, represents some sacrifice in required space (size or parts density), efficiency (power dissipation and box temperature), equipment), equipment cost (cost of added components and cooling system), and to a lesser degree, weight. As the state of the art in the use of transistors is still relatively young, more desirable protection systems or higher voltage transistors may be developed in the future. Until then, we must either eliminate the transient from the primary power source or else accept the additional components of the protective



"The properties of semiconductors are more difficult to control in production . . . resulting in a much wider spread of prduct characteristics."

systems. The reduction of primary power transients would undoubtedly improve the reliability of other components in airborne equipments."

High Power

Because of the elaborate measures necessary to cool the junction of a power transistor, and the relatively expensive components necessary to filter and regulate a low-voltage, high-current supply, vacuum tube power amplifiers will probably continue to have an economic advantage for some time to come. A modifying factor here, however, is introduced by the possibility of eliminating the output transformer in the case of low impedance loads such as the voice coil of a loud-speaker, allowing this saving to balance out the difference noted above. The choice then rests on a companion characteristic, linearity, which is easier to achieve with tubes than with transistors.

In addition to the fact that linear characteristics are easier to achieve with tubes, transistors have the added difficulty of variable input and output impedance from small to large signals, making driving and matching difficult, and adding to the distortion.

Spread and Control of Characteristics

At the present time, the properties of semiconductors are more difficult to control in production than those of tubes, resulting in a much wider spread of product characteristics. In most cases, this spread is too wide for any one intended application, requiring the selection and labeling of several different portions of the overall product falling into various groupings for gain, breakdown voltage, etc. This has produced a tremendous multiplicity of type numbers (over 700, not counting experimental), with various combinations of these properties, and, depending on the yield in each area, widely varying costs. Some of this variation will undoubtedly be reduced by further manufacturing refinements, but some of it may be inherent in the nature of the device, because of the sensitivity of the semiconducting material to extremely minute amounts of contamination. As a result, where spread of characteristics, or close tolerances, or the ability to turn out a uniform product over an extended period is a prime consideration, tubes should continue to be superior.

For example, the custom is to release a quantity of type numbers for transistors made with a given physical arrangement, and test them to identical limits and characteristics, except for one critical parameter. In other words, it is impossible to control this latter characteristic, so it must be accomplished by selection. For instance, the following groups of types are identical except for Alpha cutoff frequency!

2N444 — 0.5 mc	2N519 — 0.5 mc
2N445 — 2.0 mc	2N520 — 3.0 mc
2N446 — 5.0 mc	2N521 — 8.0 mc
2N447 — 9.0 mc	2N522 — 15.0 mc
	2N523 — 21.0 mc

This is obviously a serious obstacle to standardization.

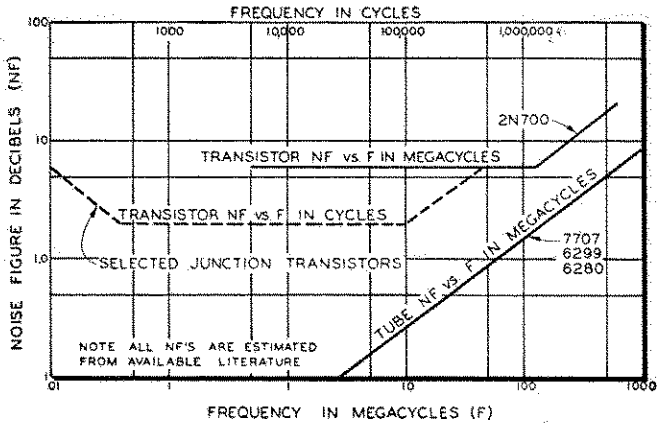
For further evidence, the following news item is of interest:

Transistor Preferred Circuits

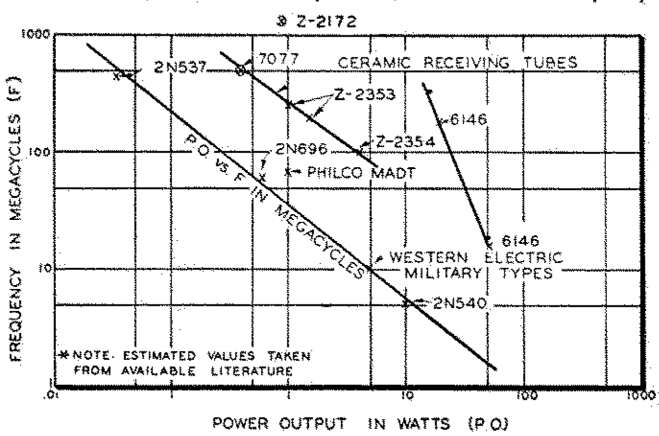
National Bureau of Standards program to develop preferred transistor circuits, similar to preferred tube circuits developed earlier, has run into a snag because of extremely wide variability of characteristics in transistors. Whereas transconductance of a group of Mil-standard tubes normally varies only ±10%, corresponding important characteristics of transistors, such as short-circuit current gain, may vary 200% or more."

Also, examination of the few MIL specifications available for transistors will reveal that they control only a very few characteristics, and these to

Tube and Transistor Noise Performance



Transistor Available Power Outputs—As a Function of Frequency



very much looser AQL values than the corresponding tube characteristics. By contrast, MIL specifications for tubes now represent an extremely good guarantee of reliability over a 1,000-hr. period.

The really basic consideration here is admirably outlined and explained by Marshall Pease, Associate Editor of The Microwave Journal, September-October 1958 issue, in an article entitled "On the Virtues of Separability—Tubes vs. Intrinsic Devices."[5] While the entire article is well worth reading, the main point is that in intrinsic devices, the various factors such as frequency, power density, coherence of electron flow, and some elements of circuitry are functions of sub-microscopic or ionic arrangements, and so inter-related as to be essentially uncontrollable. On the other hand, tube structures separate the beam forming, power producing, and frequency control functions far better, and give far more flexibility to the circuit designer.

Multiple-Unit Devices

As a corollary to the above difference in product control and variability, it is easy to see that tubes will continue to have an economic advantage in multi-function units, such as twin triodes or triode-pentodes, where such combinations in transistors would not prove practical. For example, if the yield of a particular tube element, when tested to the allowable customer limits, were 90%, the yield of a two-unit tube with random variations in each element would be 0.9 × 0.9, or 81%. Contrast this with present transistor yields in any one spread of characteristic limits of around 25%, and a twin-unit yield would become 0.25 × 0.25, or about 6%!

Nuclear Radiation

The available unclassified data show transistors to be definitely vulnerable to high energy gamma radiation, which does not affect tubes to any measurable degree. For thermal and fast neutrons, the various reports indicate that for equal dosage, glass tubes will last about 100 times as long, and ceramic tubes about 1,000 times as long as a transistor. To quote an ASTM report:[6]

"The results that have been obtained in the preliminary phase of this program can be summarized as follows:

"1. Thermal neutrons are not a major contributing factor to the deterioration of semiconductor devices:

"2. For the integrated doses used, gamma radiation causes surface damage which results in changes in leakage currents. Partial recovery may occur when the device is removed from the radiation field.

"3. Fast neutrons appear to cause bulk changes in materials.

PERFORATED PAGES!

In response to many reader requests the pages in the main editorial section have now been perforated. This will enable readers to easily remove material for their reference files. If the copy of Electronic Industries you receive already has pages removed that you want, please let us know. We'll be glad to provide the missing pages.

Table 1
COMPONENT FAILURE RATES

	Failures/1,000 Hrs./Component
Capacitors	
Ceramic	.00048
Mica	.00042
Paper	.00094
Tantalytic	.0041
Chopper, Mechanical	.114
Coils, Small RF, IF Transformers, etc.	.0021
Connectors	.0047
Crystals	
Oscillator	.0151
Rectifier	.0037
Diodes	
Germanium	.002
Silicon	.002
Filter, Line	.012
Heater	.007
Meter	.032
Motor	.023
Potentiometers	.0021
Pulse Forming Network	.0346
Relays	.0296
Resistors	
Carbon Composition	.0008
Carbon Deposited	.0013
Wire Wound	.0014
Solenoid	.0133
Switches	
Stepping	.442
Toggle	.007
Thermistor	.010
Transformer	
High Voltage and Power	.0191
Low Voltage	.0032
Transistor	.010
Tubes, Receiving	.010
Variac	.006

"4. In reactor irradiations, silicon rectifying devices which deteriorate will probably fail in the forward direction with increases in forward resistance and break-point voltage. For the integrated doses used, germanium devices generally suffer major damage in the reverse direction only.

"5. For most applications, silicon diodes and rectifiers tested could probably be used to 10^{13} nv_et, and the silicon and germanium transistors irradiated could probably withstand 5×10^{11} nv_et under the conditions of test. These limits are considerably below the limits that would be caused if radiation damage on the bulk materials above is considered. The basic processes of semiconductor devices are probably disturbed by the presence of the radiation field, causing the radiation resistance of the devices tested to be considerably lower than would be expected by considering the basic properties of the semiconductor materials."

An examination of another voluminous study, an Admiral Report, reveals this same ratio: "The 6L6WGB beam power, the 5639 subminiature video amplifier, the 5840 subminiature pentode, the 5670 miniature twin triode, and the 5876 subminiature UHF survived the irradiation, but had control grid currents in excess of the maximum specification. . . . The 6112 subminiature twin triode, and the 5751 miniature triode all survived the CP-5 experiment." From Admiral Report No. 8, Phase 1, July, 1957.) The interesting point, however, is that the transistor tolerance limit is about equal to the human tolerance limit, and that tubes are relatively unaffected at this dosage. This means that while it may be possible to evacuate personnel and protect them from an atomic explosion, it would be highly impractical to bury or shelter all electronic equipment, and if the equipment was expected to survive in operating condition, it better use tubes.

It is interesting to note that the U. S. Army Signal Corps has become concerned about this and other tactical aspects of the use of transistors in the design of military gear, including missiles, and is publishing a comparison of its own, entitled "A Report of the Current Status and Future Trends in Electronic Tube and Transistor Electronics."

Additional material may be found in "Radiation Effects in Semiconductor Devices," and "Effects of Gamma Radiation on Transistor parameters."[7]

Reliability

In terms of survival under equivalent operating conditions, there is practically no information comparing tubes and transistors directly, except for some studies by Bell Laboratories on some of their own early types. These indicate comparable figures for their best tubes and best transistors, under practically ideal operating conditions, or around 0.03% per 1,000 hours. Other less accurate figures in military gear have given about 0.1% per 1,000 hours for both.

As a practical matter, voluminous specifications, both manufacturers' and military, are available which guarantee a "floor" under allowable failure rates of tubes, and a very good probability that most lots will give better than 99% survival at 1,000 hours under maximum rated conditions, whereas such survival specifications and documented data are completely lacking for transistors. This is not to say that transistors do not have a very high *potential* reliability, possibly somewhat better than that of tubes, but that prediction, control, and statistical evidence of consistent survival under comparable environmental conditions are not yet available, and will probably take ten years to accumulate. This will render impossible any calculations of system reliability or the value of such provisions as multiple channel redundancy.

A typical list of failure rates of components in a number of military equipments is shown in Table I in the appendix, where both tubes and transistors have been used in various portions of the equipment, as well as germanium and silicon diodes. It will be noted that in this particular set of data, the tubes and transistors came out about even at 1.0% per thousand hours. It should be noted, however, that in general it takes three or four times as many transistors to perform the same functions as currently available military tube types, because of their lower gain-bandwidth factor and single-unit limitations, so that it would appear that the over-all equipment reliability using tubes is still about three to four times as good.

In fact, one example of comparable designs of a servo-amplifier required only eight tubes in the original prototype, but wound up with forty transistors in the redesigned version! Obviously, it will take a considerable improvement in the reliability of transistors to make up for this initial handicap.

There is one further feature of transistors, which, although greatly improved in the last two years since the original papers in the aforementioned Transistor Reliability Symposium, is nevertheless a serious and disturbing factor, and that is shelf life. There is, of course, the effect of storage at high temperatures, which shows definite deterioration at 85°C for germanium,[8] and also the effect of small amounts of contaminants inside the sealed enclosure affecting the surface condition of the germanium crystal.[9] As sealing, exhaust, and gettering techniques approach that of vacuum tubes, this effect will undoubtedly be reduced, but the inherently greater sensitivity of the resistivity of the semiconducting surface to extremely minute amounts of contaminants is a problem which is not, fortunately, found in tubes.

Physical Size

Transistors have an obvious advantage over tubes on both of these counts, except for ceramic tubes, but the unit itself is not the whole story. In the case of power transistors, the heat sink and radiator must be many times the size of the transistor, and may well be larger than a tube of the same output rating, since the junction temperature must be kept much lower than that of the tube envelope. Similarly, in large installations involving many thousand units, the air conditioning may have to be just as large for transistors, in spite of their lower power consumption, since the *allowable rise* cannot be as great. Heat flow and thermal calculations are fairly long and involved, so it is impossible to generalize, but this hidden factor must be borne in mind when considering tubes vs. transistors from this standpoint.

This paper was presented at the AIEE Winter Meeting, Feb. 1959.

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