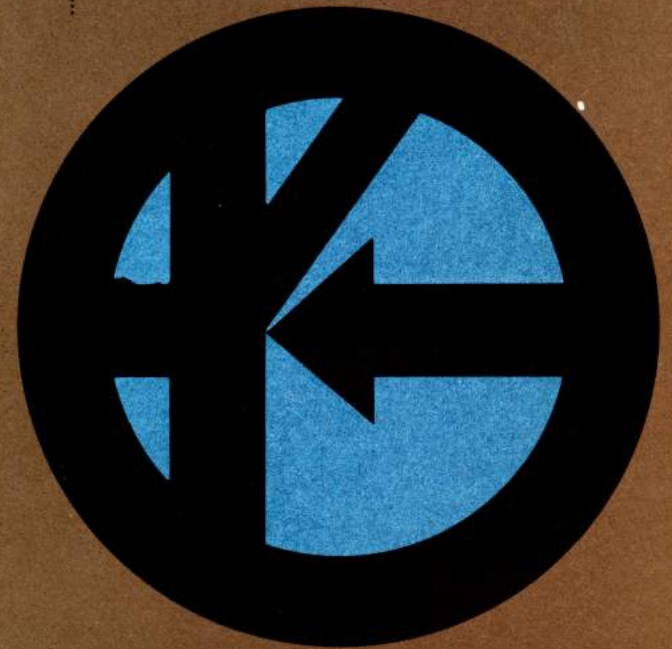




TUBES AND TRANSISTORS *a comparative study*



TUBES AND TRANSISTORS

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The Electron Tube Information Council

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TUBES AND TRANSISTORS



The Purpose of this Book

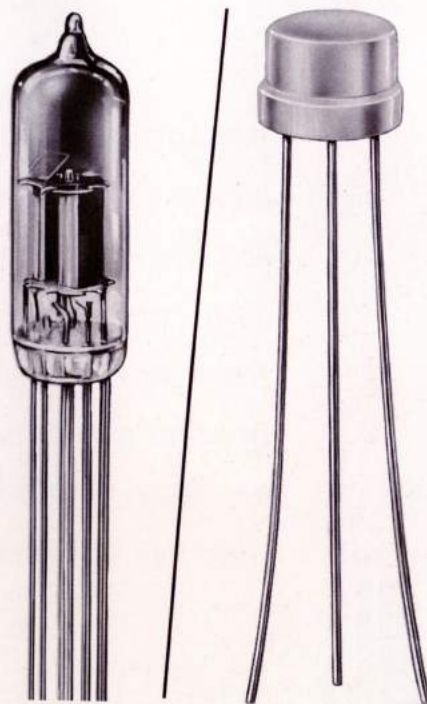
The editors have attempted to provide a thorough comparison of the two devices as a guide to rational evaluation. Management readers will find in Part 1 a review of the inherent characteristics of tubes and transistors, as well as a summary of the degree to which their potential capabilities can, in a practical sense, be realized today. Part 2 discusses the prospects for both devices against the background of their historical development. Touching upon refinements and new developments, Part 2 may suggest new design possibilities. Engineers will find the whole problem presented in terms of specific design considerations in Part 3.

Since this book cannot discuss specific applications, it will not attempt to draw conclusions in terms of individual equipment designs. It will, however, serve as a source of current information to help management and design personnel answer these questions in terms of their product requirements:

- 1. Which device offers the best combination of characteristics for equipment being designed today?*
- 2. Which device will most likely be best for equipment of the future?*

As in the case of any undertaking in the field of electronics, the treatment here must be limited by certain design parameters. Discussion is restricted to high-vacuum receiving tubes and equivalent transistors, such as those used in home television and radio equipment and in military and industrial applications.





INTRODUCTION

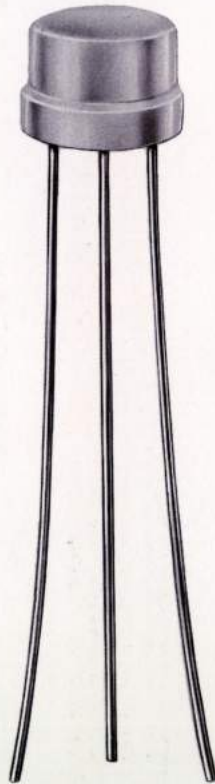
Tube or transistor? This is a basic question daily facing management and design engineers in the electronic industry. Yet, the issue is relatively new. Until 1948, the choice of active components had to be made among the various innovations in electron tube design. ➡ Then, the transistor entered the scene, bringing with it dramatic possibilities for miniaturization and lower power consumption. With it came predictions of unlimited reliability, reduced

costs and eventual adaptability to every known application involving electronic control and amplification. ➤ Virtually all electronic systems since have been scrutinized to determine whether they could or should be transistorized. Certain long-standing concepts of circuit design have been revised to accommodate the benefits of solid-state physics. Fresh approaches to equipment



packaging have evolved. Several new product concepts have emerged as a direct result. ➤ As the designer saw the transistor begin to mature as a component it became increasingly difficult for him to separate its future promise from its present usefulness. ➤ Meanwhile, an evolution of comparable significance was quietly taking place in the design of electron tubes. While the

systems engineer was trying to judge the potential capabilities of transistors against the known standards of the electron tube, those standards were changing! Continued reductions in tube size, higher standards of reliability, new cost savings through automatic processing, and new performance capabilities combined to increase the engineer's dilemma. ➤→ There has not yet



been sufficient pause in the simultaneous development of the two devices to permit the industry to get its bearings. The result has often been misapplication, waste and degraded performance. Today, engineers disagree on the relative merits of tubes and transistors for specific applications. The time has come for a comprehensive appraisal of the two devices.

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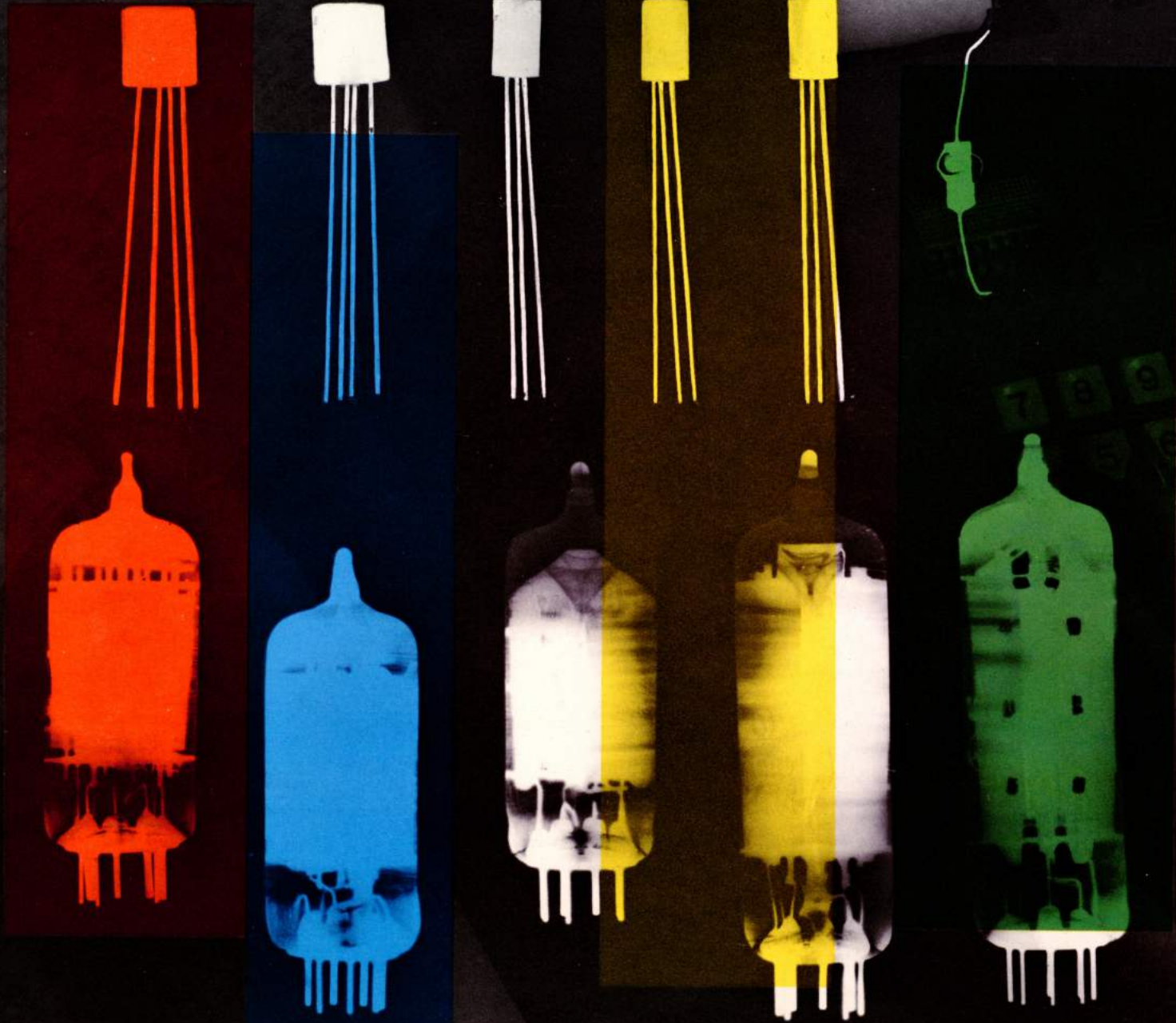
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PART 1 TUBES & TRANSISTORS TODAY



TUBES AND TRANSISTORS TODAY

TUBES OR TRANSISTORS?

Though each device has its own advantages and disadvantages, the rapid pace at which both components are being developed makes comparisons and rational selections increasingly difficult. Actual attainments and predicted accomplishments become intermixed; fact and fancy become harder to separate. Yet, in the development of every circuit there comes a time when the design must be finalized and components selected on the basis of what is presently offered, regardless of what may be "just around the corner."

This section of the book compares tubes and transistors on the market today. The facts are presented in terms of the performance and economic considerations which are of major importance to management. Detailed information in support of these facts is presented in Part 3.

reliability

When choosing a component the important thing to consider is practical, not theoretical, reliability. By this is meant the ability of the component to operate satisfactorily up to the intended lifetime of the equipment in which it is used.

Infinite inherent life has frequently been claimed for the transistor on the assumption that no significant wear-out mechanism is present, whereas the chemical reaction associated with cathode emission in the tube would eventually go to completion. Analysis of available evidence, however, clearly indicates that either device can exhibit outstanding reliability if it has been properly controlled during manufacture and if it is correctly applied in equipment. Still, failures occur. Transistor failures are usually caused by changes in basic parameters and by interelectrode leakage. Tube failures can most often be traced to interelectrode leakage, changes in characteristics, and breakdown of the heater-cathode system.

Comparative evaluation is difficult, because the two devices do not share the same standards of reliability measurement. Tube reliability data are taken from field experience whereas transistor data are based largely on laboratory performance, expressed in terms of "potential" reliability. Even where field operating data on both devices are available, comparison is speculative because of the relatively limited amount of evidence available for transistors.

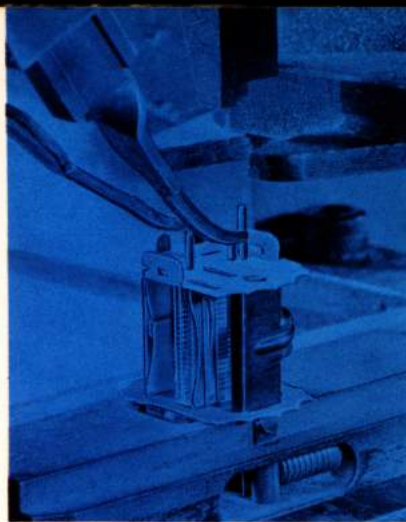
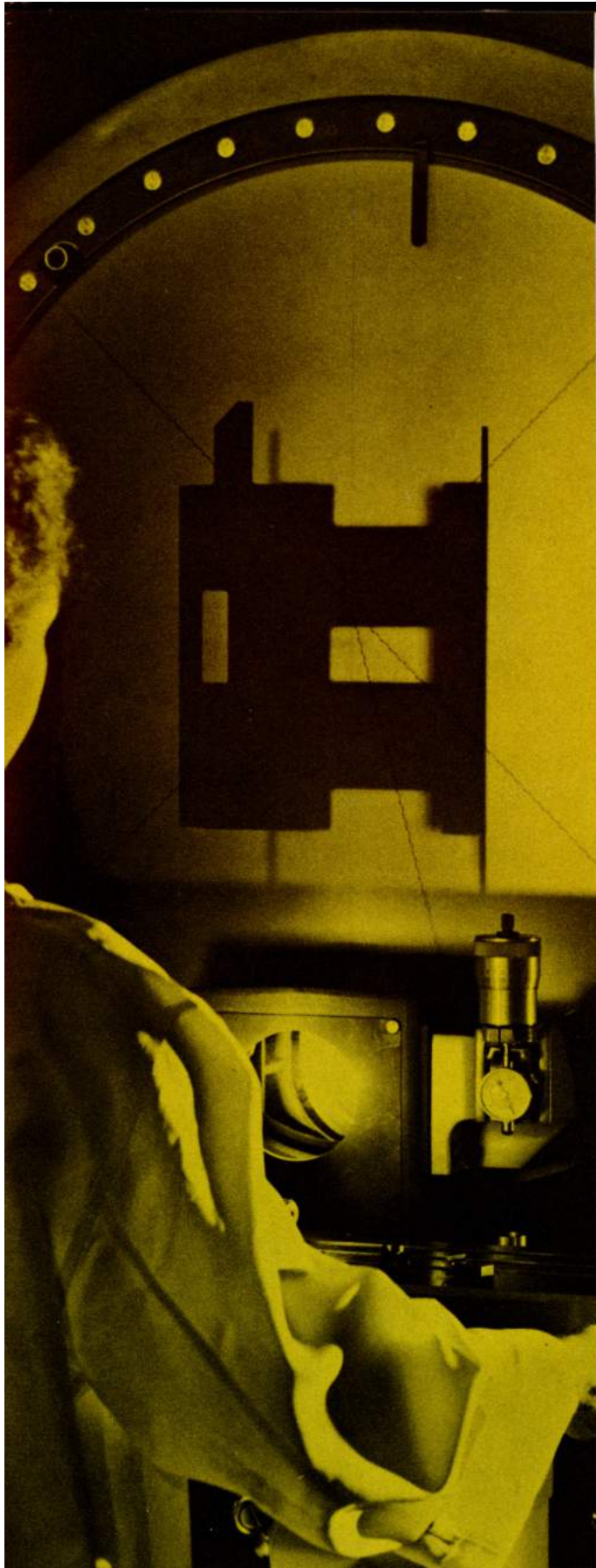
temperature capability and stability

Although the temperature environment for electronic equipment is a critical factor, ambient temperatures within the range of human comfort pose no problem for tubes or transistors if adequate thermal-design criteria are employed. It is under conditions of elevated temperature and temperature variation that significant performance differences occur.

Electron-tube internal parts normally operate at levels well above the ambient temperatures encountered in most applications. Thus, their performance characteristics are relatively unaffected by either high temperature or temperature variation. Conventional glass tubes operate successfully and provide maximum performance at 200°C, and ceramic tubes operate safely and provide full performance at more than 400°C.

Transistor action, however, is seriously affected by thermal excitation, since the limiting physical characteristic of solid-state devices is the temperature of the junction. Transistor temperature limitations for this reason are normally expressed in terms of junction temperature rather than the somewhat lower ambient temperature. Most transistors can operate safely at junction temperatures no higher than 100°C, at which point useful output is limited. Even the best silicon transistors provide full dissipation capability only to junction temperatures of about 150°C, or about 100°C ambient. They are disabled somewhat above this temperature.





Automatic assembly of tube cages



Transistor manufacturing

Tube quality control inspection



Temperature variation also causes instability in transistor operation. The designer can usually provide compensation for this characteristic, but he may in the process reduce maximum usable performance and be forced to add more transistors and associated circuitry.

Storage temperature is another factor to be considered in evaluating the two devices. Tubes are able to endure prolonged storage without being affected by temperature while transistors tend to deteriorate under the same conditions.

environments

Tubes and transistors have both demonstrated ability to withstand vibration and other mechanical hazards such as shock and spin. There exists, however, a significant difference in their ability to resist the effects of radiation.

Radiation exposure can easily cause temporary or permanent damage to a transistor, since its basic medium of energy transfer is a solid-state molecular structure whose arrangement is easily disordered by both gamma rays and neutrons. The electron tube, on the other hand, can withstand much higher amounts of radiation exposure without damage. Equipment to be located near nuclear engines or reactors will require considerably more shielding if transistors, rather than tubes, are used.

Once exposed to a short pulse of radiation, transistors may never recover or may recover only a portion of their original performance level. Under similar conditions, tubes will usually recover fully.

spread of characteristics

Transistors are at a disadvantage with respect to spread of characteristics because of the difficulty of obtaining a highly-ordered crystalline structure and maintaining it throughout the

manufacturing process. As a result, their major electrical characteristics, in general, show a much wider deviation from design center than do those of tubes. Thus, the user may find he cannot interchange similar types made by different manufacturers. Or he may be forced to pay a premium for transistors specially selected with the narrow tolerances needed in his particular application.

Tube manufacturing processes and the tube's active elements and parts are more easily controlled. Similar types made by different manufacturers may be interchanged freely.

power-handling capabilities

Tubes and transistors differ radically in their comparative power-handling capabilities. Basically, of course, the tube is a voltage-controlling device; the transistor controls current. Tubes are inherently better suited for high-voltage application, particularly where high impedance is required. Transistors are superior for applications involving low-voltage inputs with low impedance.

Exceeding even momentarily the maximum ratings of voltage and current tends to produce more serious effects in transistors than in tubes. The tube may be able to operate with satisfactory performance under these conditions, although life expectancy will be reduced. Transistor failure is usually catastrophic and immediate.

Since the transistor, in contrast to the tube, requires no heater power, it is generally preferred for portable devices or any other application where low power requirements are of major importance.

input-output capabilities

Tubes are normally more suitable than transistors when the primary objective is to amplify voltage. They require less driv-

ing power, need not be drift compensated, have higher characteristic gain, and display more usable characteristics at higher frequencies. In addition, tube performance is generally more linear over a wider range of signal amplitudes. The degree of nonlinearity is predictable, so that design measures can easily be taken to remedy it.

Transistors are inherently nonlinear, particularly with variations in ambient temperature and load impedance. Under these conditions circuit compensations are usually required.

high-frequency capabilities

Tubes provide higher power and gain, especially at higher frequencies, than do transistors.

Transistors have an inherently limited power gain and unavoidable internal feedback. They are characterized by the appreciable transit time of the useful carriers traversing the base region, by collector capacitance and by base resistance. Overcoming these basic limitations to give transistors high-frequency performance capability usually involves a considerable process of selection and arduous circuit design.

noise

Electrons move much more slowly through a solid state than through a vacuum. Thus, the base-collector diffusion process of the transistor is slow and noisy by comparison with the free electron flow in a tube. However, practical considerations are not this simple. Based on an analysis of the important factors contributing to noise in tubes and transistors, the following conclusions can be drawn:

Random noise output is inherently lower in tubes than transistors when they are compared on a noise-power basis. This holds true despite microphonics and leakage effects.

For general audio use, transistor circuits having relatively lower noise levels can be designed using special selection of

transistors. Transistors perform well in the low-level stages of preamplifiers, where hum and microphonics are critical considerations.

In the mid-frequency range, above audio and below approximately 500 kc, tubes are generally less noisy.

For low-level signal applications where a noise level approaching theoretical minimum is desired, tubes are best. For ultra-high-frequency applications, the tube is unchallenged.

size and weight

Transistors are inherently smaller and lighter than tubes, and deserve first consideration whenever miniaturization is the primary objective. There are certain instances, of course, where measures necessary to counteract the transistor's heat sensitivity or provide equivalent electrical performance cancel out the transistor's size advantage and result in a circuit as large as one employing tubes.

cost

Tubes are less expensive than transistors by a ratio of about 2 to 1 for most industrial and entertainment types, and by a greater ratio for military types because of the specifications involved.

logistics

Tubes of most types are available from several suppliers, and replacements are readily available to the user. Interchangeability, especially important in military applications, enables the tube to fit into the "pipe-line" concept of support necessary for the preservation of equipment effectiveness. Tube maintenance is simpler, due to the mechanical ruggedness of the device, its mode of mounting, and its high resistance to temperature and electrical damage. The tube's longer storage life under

a wide range of conditions also contributes to greater availability.

Transistors have not attained the degree of standardization that tubes have reached. Interchangeability generally requires special selection processes and is usually limited to non-critical applications. Transistor servicing always carries with it the threat of damage caused by heat from soldering irons, inadvertent application of current surges, or faulty test equipment.

SUMMARY

The foregoing facts make it abundantly clear that there is no universal answer to the question: tubes or transistors?

From the standpoint of over-all electrical performance, certain design sacrifices must be made in order to achieve proper operation with either device.

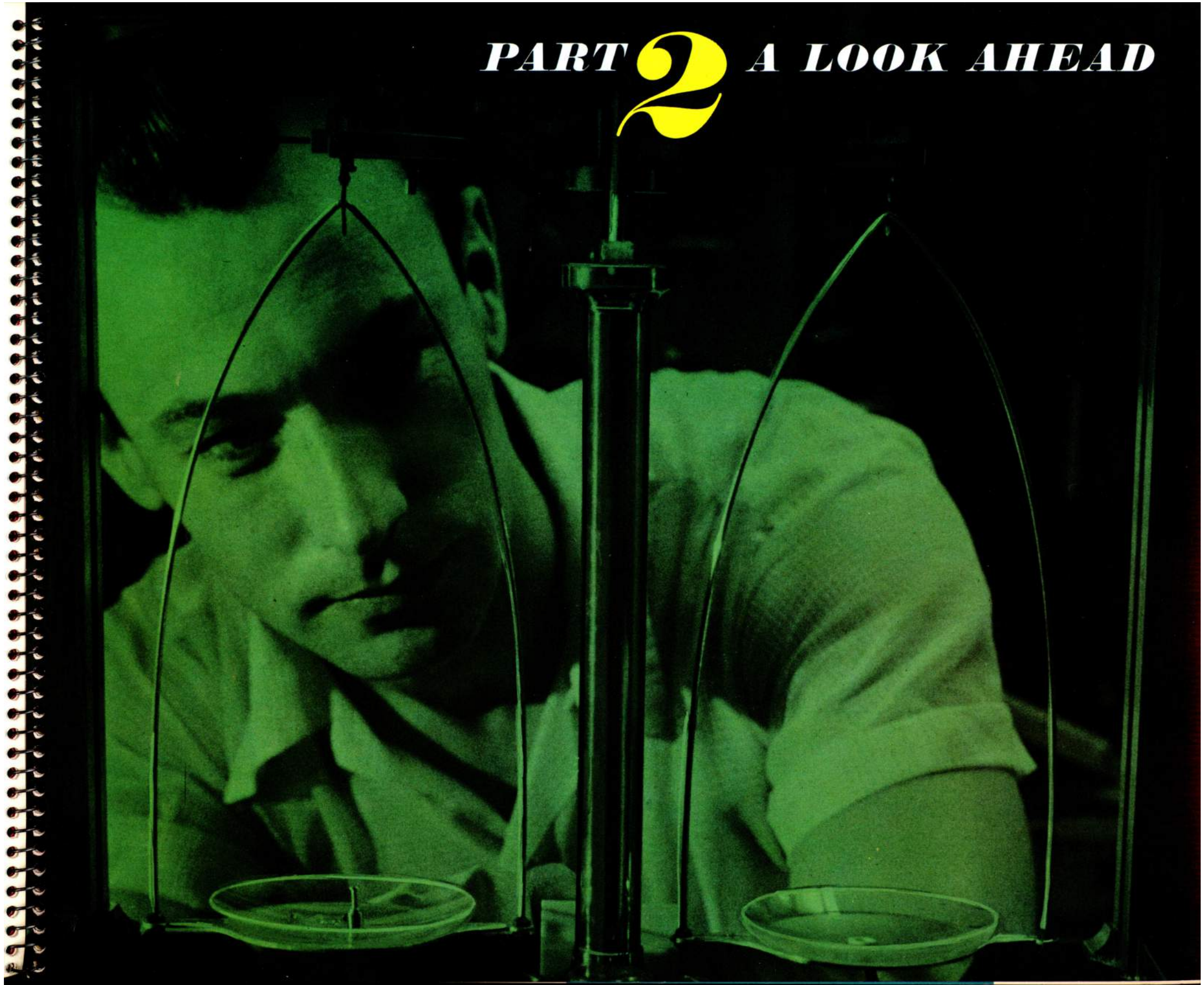
Circuit designers using transistors must accept a considerable reduction in performance to compensate for temperature ambients, temperature changes, wide spread in characteristics, low input impedance, nonlinearity and electrical instability. The designer must provide extensive additional circuitry, both active and passive, to overcome these liabilities.

Circuit designers using tubes must provide for heater circuitry and for the power which must be applied to the cathode to support thermionic emission.

Both tubes and transistors, when properly applied, can provide reliable service. Transistors are superior in terms of size and weight. Where cost, high frequency, or logistical considerations are paramount, tubes have the advantage. There are several areas where neither device enjoys a marked superiority and where features overlap.

Always, the choice must depend upon the application.

PART 2 A LOOK AHEAD



PROGRESS IN TUBES AND TRANSISTORS

Newness is a competitive necessity for manufacturers of electronic equipment, and they have demanded a steady rate of progress from component manufacturers. As a result, the electronics industry has always been characterized by the rapidity of its product developments.

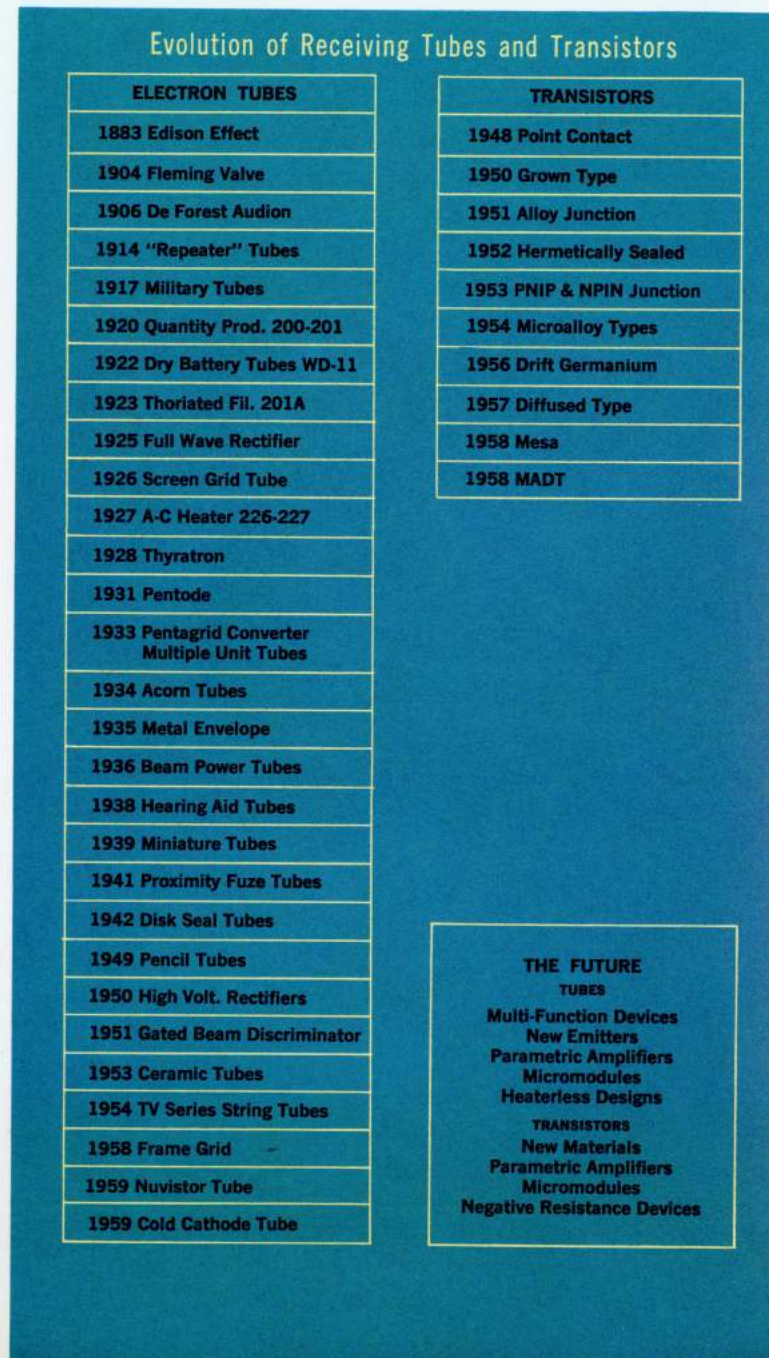
The invention of the triode in 1906 set off a rapid succession of tube advances, each one followed in short order by new and sometimes radical equipment designs. Within twenty years, power oscillators, dry-battery tubes, thoriated filaments, and special-purpose tubes were in common use. By 1926, the screen-grid tube had appeared on the market. This important contribution to tube design minimized the oscillations due to feedback, thereby providing an excellent amplifier. A year later another innovation, the a-c heater, made it possible to operate a radio directly from household electric outlets.

The new designs of the 1930's—pentagrid converter, beam power tube and multi-unit tube—all helped reduce costs as well as circuit complexities. At the same time, probably as a result of the accelerated rate with which these innovations materialized, design experts and equipment manufacturers became aware of the growing need for a more dependable product. Thus, the concept of reliability, and criteria to maintain it, were set up more than twenty years ago. These criteria have, of course, kept pace with advances in the industry ever since.

The arrival of the transistor in 1948 was announced discreetly in a news release from the Bell Telephone Laboratories. A rapid succession of transistor developments has since precipitated a host of electronic breakthroughs. Most obvious of these have been benefits to the consuming public through the miniaturization of hearing aids, pocket radios, etc. In the military field, exciting developments such as battery-powered space satellite equipment have been made possible by the low drain and high efficiency of certain semiconductor devices.

The impact of the transistor on the electronics industry in one short decade has been extraordinary. At first, some designers saw in the transistor the beginning of the end for the vacuum

FIGURE 1





Transistor assembly

tube. The sudden and wholesale transistorization of many equipments was advocated. History, however, points to few cases where a new development actually has had such pronounced effects on its predecessor. The highly efficient fluorescent lamp was at one time expected to supersede the incandescent bulb. Yet today, incandescent lamp sales are booming. Phonograph popularity has continued to soar in the face of competition from radio, and radio is still growing despite television.

Since the transistor followed the tube and added certain electronic capabilities, many presumed it would be the dominating device of the future. By the same token, had the tube followed the transistor, the tube's superiority in important characteristics might have encouraged many engineers to scrap transistors. In fact, at one time electron tubes did supersede a semiconductor device, and it has been many years since the galena-and-cat's-whisker radio has been anything but a toy.

Today, we know that neither tubes nor transistors will take over the market this year, or even five years from now. Each has too many exclusive advantages. But what about ten years from now? Or twenty-five?

Progress usually moves in parallel paths. The development of tubes and transistors is not likely to provide an exception to the rule. New designs, new materials, new manufacturing techniques come forth with increasing frequency; yet the ultimate development of these electronic devices is still far out of sight.

The circuit designer's dilemma: On the one hand, he finds himself in the happy position of having two dynamic sources of new ideas and new components. On the other hand, he faces the baffling task of keeping up with a cascade of new developments and of separating practical from "blue sky" predictions.

In this section the editors will examine recent developments in tubes and transistors. The cadence of contemporary activity is leading toward additional improvements. The editors will venture to highlight these too.

Testing transistors at the rate of 1600 per hour ➤



ELECTRONIC TUBE PROGRESS

The significant progress in tubes in recent years follows two avenues of improvement: Increased circuit capabilities and increased environmental tolerance and reliability. Greater capabilities include such features as exceptionally high frequencies, higher power efficiency, notably higher transconductance, and smaller size. Greater environmental tolerance and reliability apply to all classes of tubes and come from redesign, new materials, and new manufacturing methods.

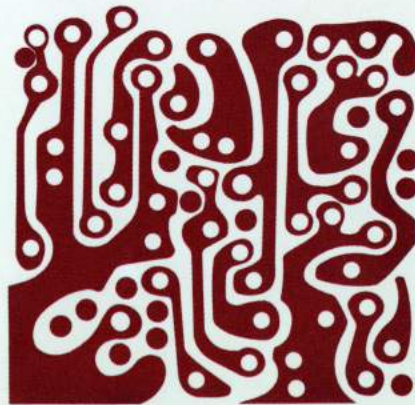
New tube designs can withstand thermal stresses far greater than the limits of safe operation existing a year ago. Frame-grid construction takes its place with other developments such as planar and cylindrical designs, ceramic-spaced structures, metal-to-glass seals and metal-to-ceramic seals. Many of these advances are embodied in the nuvistor and other new sub-miniature designs which promise new levels of heater efficiency and unprecedented resistance to shock, vibration and extremes of temperature.

Tube ruggedizing, particularly with respect to missile requirements, has been another area of significant achievement. One example is the ceramic tube. This ultra-high temperature, shock-resistant unit should insure the availability of active elements needed to meet the military's most extreme application requirements.

New materials which have significantly extended tube performance and life include synthetic micas, three- and five-layer composite anode metals (which achieve better anode temperature distribution), self-gettering coatings and structural materials, and ceramic envelopes.

Advances in glass technology have produced a boron-free envelope, with higher temperature capability and even greater resistance to nuclear radiation. The introduction of vacuum-melted alloys is another example of refinement of tube materials.

New manufacturing techniques include the "Sarong"^{®*} (film-wrapped) cathode, the adaptation of automation, and the perfection of exhaust techniques for electron tube processing. Some of the new methods have improved the vacuum level of production equipment by a factor of about 1000.



Specifications for Tube Type No. 6AK5 Issued in 1950

ACCEPTANCE TEST	AQL (%)	LIMITS	
		Min.	Max.
1. Vib (G=2.5, F=25 cps)	6.5	—	600mV
2. I _f	6.5	160	190ma
3. I _{hk}	6.5	0	30μa
4. I _{c1}	0.65	0	-0.1μa
5. I _{b(1)}	0.65	3.0	12.0ma
6. I _{b(2)}	0.65	0	200μa
7. I _{c2}	0.65	0.8	4.0ma
8. S _m	0.65	3500	6500μmhos
9. ΔS _m (E _f =5, 7V)	0.65	—	15%
10. RFN (E _{sig} =30mV)	0.65	(objectionable noise)	
11. Capacitance			
C _{g1-p}		—	.020μμf
C _{gk}	6.5	3.4	4.4μμf
C _{pk}		2.45	3.25μμf
LIFE TEST			
Intermittent Life Test	80% minimum rating at 500 hrs.		
Intermittent Life Test End Points	S _m =2900μmhos; Inoperatives		

Specifications for Improved Version of Tube Type No. 6AK5 as it appeared in 1958

ACCEPTANCE TESTS	AQL %	LIMITS				ALD	LIFE TESTS	Min.	Max.
		Min.	LAL	UAL	Max.				
1. I _f	0.4	160	168	182	190	14ma			
2. I _{hk}	0.4				10	μa			
3. I _{c1}	0.4	0			-0.1	μa			
4. I _{b(1)}	0.4	5.0	6.5	8.5	11.0	2.5ma			
5. I _{b(2)}	0.4				200	μadc			
6. I _{c2}	0.4	0.8	1.9	3.1	4.0	1.4ma			
7. S _m	0.4	3800	4500	5500	6200	1025μmhos			
8. S&C (DC Short Test)	0.4								
9. Mechanical (New Proposal for Reliable Miniature Tubes)									
10. IR									
R _{g1-all}	2.5	100				Meg			
R _{p-all}		100				Meg			
11. I _{b(3)}	2.5	5				μa			
12. ΔS _m / E _f	2.5				15	%			
13. I _{sc1}	2.5				-0.5	μa			
14. RFN (E _{sig} = 15mV)	2.5				3.0	mw			
15. N & M	2.5				175	mV			
16. Capacitance									
C _{g-p}					.02	μμf			
C _{in}	6.5	3.4	3.6	4.4	4.6	0.75μμf			
C _{out}		2.45	2.6	3.1	3.25	0.50μμf			
17. Low Pressure Voltage Breakdown (Monthly)	6.5								
18. Vib (G=10; F=40 cps)	6.5				200	mV			
19. Shock									
Vib					300	mV			
I _{hk}					30	μa			
S _m		3500				μmhos			
I _{c1}		0			-0.2	μa			
20. Fatigue (Monthly Test)	6.5	(Limits same as Shock)							
21. Base Strain Test									
22. Glass Strain Test	2.5								
LIFE TESTS					Min.	Max.			
Heater Cycling Life Test (2000 cycles)									
I _{hk}						20μa			
Stability Life Test (2 hrs. & 20 ± 4 hrs.) Same limit									
ΔS _m 1% AQL						10%			
LIFE TESTS									
Survival Rate Life Test (100 hours)									
Inop.		.65% AQL	(Repeating DC Short)						
S _m		1.0% AQL	3550					μmhos	
Intermittent Life Test (165°C Bulb Temp.)									
Life Test End Points at 500 hrs.									
Allowable Defects Per Characteristic Combined					1st Sample	Sample			
1. Inoperatives					1	3			
2. I _{c1}					1	3	0	-0.1μa	
3. I _f					1	3	160	193ma	
4. ΔS _m / E _f					1	3		20%	
5. ΔS _m / E _f					1	3		15%	
6. I _{hk}					1	3		10μa	
7. IR									
R _{g1-all}					1	3	60	Meg	
R _{p-all}							60	Meg	
8. Avg. ΔS _m / E _f								15%	
Total Allowable					3	6			
Life Test End Points at 1000 hours.									
1. Inoperatives					1	3			
2. I _{c1}					1	3	0	-0.1μa	
3. I _f							160	196ma	
4. ΔS _m / E _f					1	3		25%	
5. I _{hk}					1	3		10μa	
6. IR									
R _{g1-all}					1	3	50	Meg	
R _{p-all}							50	Meg	
Total Allowable					4	8			

future developments

Current development work is aiming for production of such idealized types as heaterless tubes, self-heating tubes, and cold tubes. Some of these developments seem to be right around the corner. For example, there exists today a prototype high-vacuum, cold-cathode tube, whose operation is based on evoking a secondary electron emission from a thin cathode coating of magnesium oxide.

Another innovation, soon to enter the market, is the "match-box" tube. This design, being developed in triode and pentode types, will be especially adaptable to use in printed circuits. The unique structure allows it to be freely supported by its leads, with the tube itself soldered in place in the recessed circuit board.

A new concept of structurally integrating tubes and associated circuitry into one tiny ceramic module is another important step toward greater miniaturization and environmental tolerance for military requirements. Film resistors encapsulated within ceramic insulators and micro-miniature capacitors are built into the module. A complete circuit, such as an amplifier or multivibrator, occupies a space no larger than a pencil eraser. This device, called TIMM for Thermionic Integrated Micro-Module, actually utilizes the heat generated in compact electronic equipment. The design differs from other micro-modular concepts in two respects: 1. Very small heaterless electron tubes are used. 2. Auxiliary cooling requirements are reduced or eliminated, since heat losses generated in the equipment serve the useful function of increasing efficiency. This unique approach also contributes to the life and reliability of the equipment.

future reliability

Prospects for electron-tube reliability are excellent. Current developments in five major areas of tube design will soon help set new standards of tube reliability.

ENVELOPE

New materials, such as ceramics and metals, and new forms of glass have higher temperature capability and a better safety factor in dissipation characteristics. In addition, these improved envelope materials permit a more absolute vacuum, thereby leading to improved performance, greater stability and longer life.

GETTER

Combining gettering materials with tube elements will simplify tube structures and increase reliability.

HEATER COATING

Research in closer control of heater coating materials promises substantial decreases in heater-cathode leakage and hum.

CATHODE SLEEVE

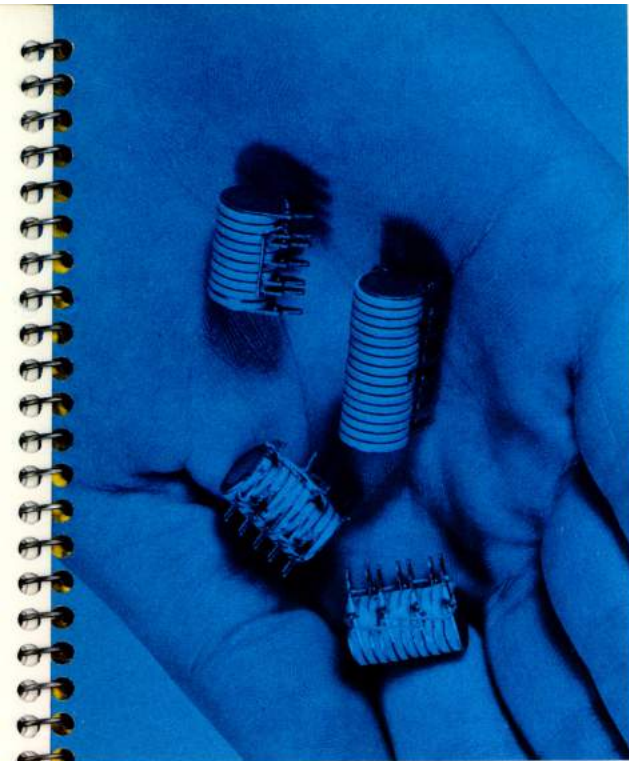
New designs and the effects of tracer elements in the cathode sleeve upon the emitter should lead to striking gains in electron tube life.

EMITTER

New emissive materials and additives should result in longer life, higher performance, and cooler cathodes.

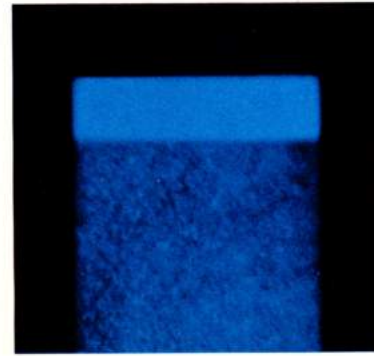
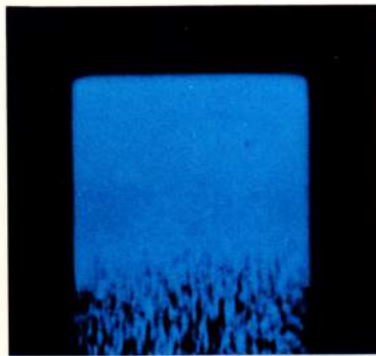
prospects for miniaturization

Research has already proved the practicality of reducing size while increasing efficiency. A number of new tube concepts and developments document this. Standard subminiature tubes, including such advanced examples as the nuvistor tube, are probably much larger than current electronic theory indicates they need be. Tube elements—cathode, grid and plate—hardly larger than a grain of wheat should be able to provide the performance required in about 90 per cent of all small-tube applications. Although reduced size will create design problems in preserving internal operating characteristics, past experience indicates that these problems too will be surmounted.



TIMMS – a new concept of microminiaturization

Testing a new tube design



Coating uniformity of new "Sarong" cathode, right, compared with conventional type

Nuvisitors are lowered into exhaust and sealing machine



TRANSISTOR PROGRESS

Transistor technology has continued to advance throughout its relatively short lifetime. Performance levels have been consistently improved, and new materials and better processing methods have resulted in broader transistor applications. Studies seeking more stable transistor materials and investigations of the action within the device are enabling manufacturing engineers to establish better control of its characteristics.

Remarkably efficient heat sinks and the introduction of materials with more advantageous thermal properties are striking at the problem of heat dissipation. Germanium transistors, for instance, are now operating at junction temperatures of more than 100°C; laboratory silicon units have reached 160°C.

The development of diffused-base, high-frequency transistors has raised the useful frequency limit for transistor amplifiers and oscillators to about 200 megacycles. Improved designs should extend the transistor into UHF applications. One prototype device, for example, was recently announced as operating at frequencies up to 300 mc with a power gain of 10 db at 1000 mc.

new designs

For high-speed switching applications, such as in digital computers, the new MADT's (Micro-Alloy Diffused-base Transistors) will prove extremely valuable. Because they have no intrinsic base region, they can maintain high-speed switching characteristics up to their saturation voltages. This will provide the advantages of direct-coupled circuitry without impairment of switching speeds.

The development of the mesa transistor is an important step toward reducing other critical transistor problems—susceptibility to radiation and limited high frequency capabilities. From a construction standpoint, mesa structure techniques also result in units of greater ruggedness. The chief advantage of these structures lies in mounting the wafer directly to the header, achieving maximum mechanical strength and heat dissipation.

new developments

Recently developed silicon carbide units and other types of material such as gallium arsenide may be able to extend the temperature range of semiconductor devices significantly.

Another development is photoetching as a means of producing transistor circuits in large quantities and with high uniformity. These printed circuit transistors open new avenues to further miniaturization. Reports indicate that units only 1/20 inch wide and 1/100 inch high are possible.

better processing techniques

Graphite parts, used extensively during many critical phases of semiconductor processing, are now being produced in extremely pure forms. The dangers of contamination from elements such as boron are practically eliminated by heating the graphite in special reactive atmospheres.

Better and faster sealing through pressure brazing techniques have helped reduce contamination during production.

Vacuum deposition techniques, which form the metallic material in extremely thin, uniform layers, now are being used. The new mesa design employs this technique, and another new process, micro-alloying, has created the micro-alloy diffused-base transistor.

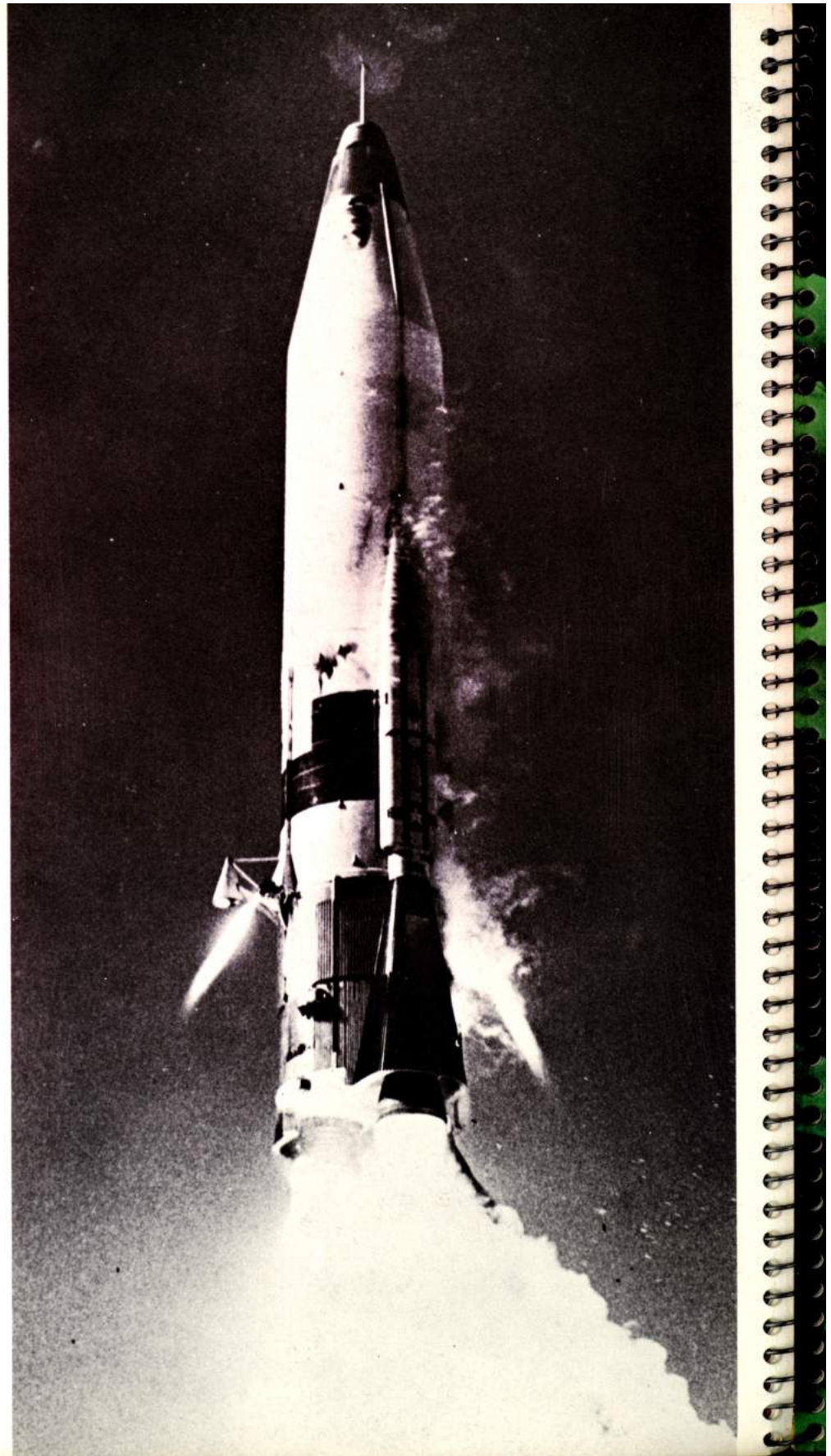
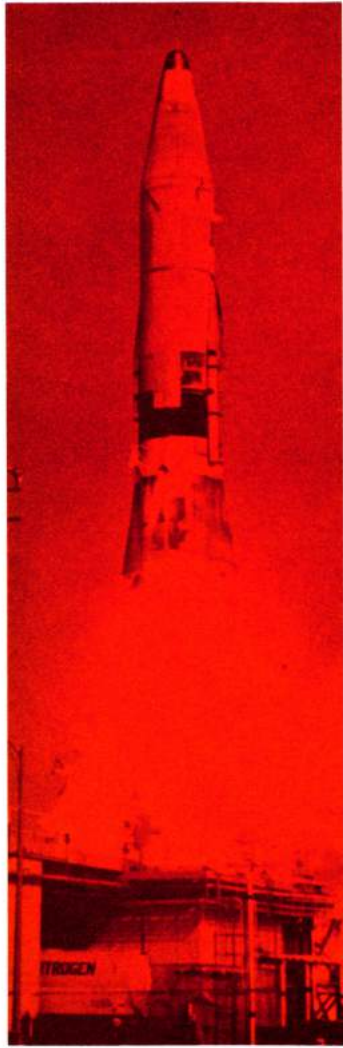
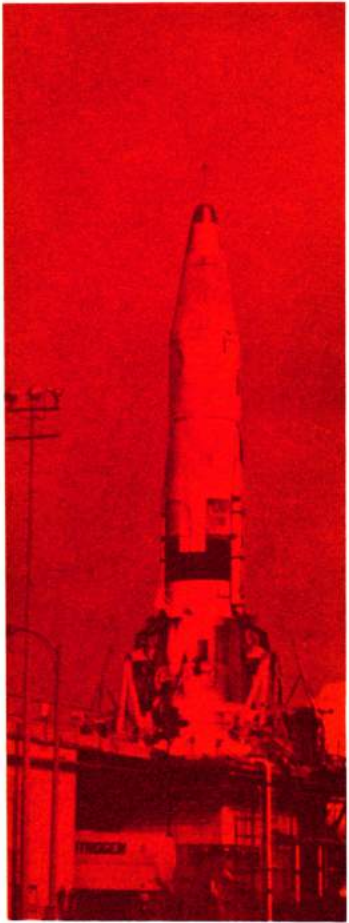
To meet the challenges of reliability and standardization, automatic testing methods are being developed. These techniques will also be a factor in reducing unit prices to more competitive levels for a number of applications, especially in the entertainment field. The use of X-ray equipment for quality control is being introduced, making possible the examination of the crystal structure of coatings laid down by vacuum evaporation. Quality control and research also benefit from infrared inspection methods.

the future

Further advances in microminiaturization through transistor technology are possible. As presently conceived, electronic micro-modules could be comprised of tiny flakes or layers of conductive, semiconductive and insulating materials. Transistor elements are suitable for this type of processing, which could result in integrated circuits much smaller than present miniaturized components. Size would be limited primarily by ability to radiate or dissipate internally generated heat.

Development of the tunnel diode concept may extend solid-state temperature capabilities.





PART 3 DESIGN CONSIDERATIONS
a guide to rational evaluation



Life testing electron tubes →



RELIABILITY

The major objective of the electronics industry is to produce systems, both military and commercial, that will operate reliably in any environments in which they are used. Constant efforts are being made to trace and eliminate the factors which cause failure . . . or at least develop accurate methods of predicting their occurrence. Since tubes and transistors are the key components in all electronic systems, their reliability is vitally important.

The definition of reliability most widely used is: "*The probability of a device fulfilling its purpose satisfactorily under the operating conditions encountered for the period of time intended.*" Customarily, this probability is based on previous experience which can be expressed in terms of a forecast of future performance.

Predicting the reliability of newly developed devices, as yet unproven in extensive field service, is a major problem. Before the designer makes any assumptions he should study compilations of laboratory life test data, application data and preliminary field failure rates. If he relies heavily on how new devices *should* perform, rather than how they *do* perform, he can find himself in serious difficulty.

criteria for comparison

For many years, tube specifications and production tests have been regarded as effective criteria for determining reliability. In contrast, transistors are relatively new; specifications are still being established and cannot be used as the criteria of reliability to the same degree as they can with tubes. While it is expected that a standardized method for measuring transistor reliability eventually will evolve, there is at present no equivalent basis for comparison with tubes.

The usual concept for measuring electron tube reliability indicates that a tube fails when *for any reason* it becomes inoperative or goes outside its specified performance limits. From a theoretical standpoint, extremely high reliability is possible. However, practical considerations of material variations, man-

ufacturing repeatability, and the possibility of misapplications are not ignored.

potential vs. actual reliability

From the start, electron tubes have endured a dubious reputation in the area of reliability. As the universal component, they suffered through the growing pains of every new electronic system. Even today, whenever there is trouble tubes are usually suspected first—if for no other reason than their being the easiest components to remove and replace. Their reputation is colored by the cumulative failures of the past.

Transistors, on the other hand, were credited with having inherently infinite reliability. This initial evaluation, however, came from the laboratory, not the field. It was theory rather than practice which established the "potential" reliability of the transistor. Actually, if the same criteria of reliability were applied to both devices, there would be no real difference in their "potential" reliability.

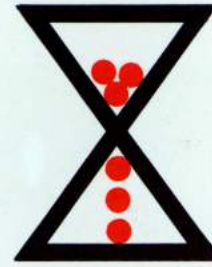
"Potential" reliability sometimes is cited by theorists as a compelling basis for the choice of one device over another. It is argued that production refinements eventually will justify the decision despite actual reliability at the current state of development. Such thinking is based on two assumptions:

1. Failures due to variations in material, processing and design will be overcome before production components are delivered, and the device will thus operate to "wear-out."
2. The device will be employed by the designer or user *only* in a manner that will allow it to reach maximum reliability.

Too often, semiconductor reliability is interpreted in terms of this "potential." In contrast, tube reliability is interpreted from experience. For consistency, comparable units of reliability measurement should be used to evaluate the two devices.

comparison from systems viewpoint

Reliability comparisons are meaningful mainly in relation to entire systems. Many types of tubes and transistors are con-



tinuously used in a broad range of applications and under varying electrical and environmental conditions. In every case, system reliability is determined by the manner in which the individual component is applied. Reliability measurements taken from one area of service cannot be assumed valid for others.

Even with reliable components it is possible for an entire system to be unreliable. The responsibility of the equipment designer cannot be overestimated, for if he uses the device beyond its ratings or without fully considering its environment, or if he relies on unconfirmed parameter values, equipment lifetime will be greatly shortened.

Because tubes have been integral and synonymous with progress in the entire electronics field, the circuit designer can find a wealth of information to help him. Documented data on the subject of getting assured reliability is readily available, and manufacturers also offer consulting services toward this end. As a result, most designers have learned the benefits of correct use of electron tubes. Nevertheless, some marginal applications do occur. In a recent survey of one area of receiving tube service—guided missiles—the very few existing misapplications accounted for a surprising *85 per cent of all tube failures*.

Application technology for transistors is not as well advanced, and transistors are sometimes unwittingly used in circuits not suitable for them. In such instances, they cannot be expected to perform reliably at full rated values. Part of the problem stems from the fact that many designers have been in the habit of working with electron tubes for which published ratings normally mean that full performance can be obtained up to the cited values. Information now becoming available as a result of the quest for transistor reliability should be of considerable assistance in the future.

reliability evidence

As was mentioned previously, statistics comparing tube and transistor reliability under equivalent operating conditions are

virtually impossible to obtain. Until such evidence becomes available (perhaps not for several years), the designer must draw his conclusions on the basis of individual performance data collected for each device separately. The most significant of such data is presented here.

Typical life test data attained with a commercial tube type and one of special design are shown in Figure 3. From this it is obvious that even without anticipated improvements in physical and chemical technology, tubes today are capable of extremely long lifetimes. Reliability attainments based on the actual life characteristics of tubes and transistors used in communications service are shown in Figure 4. This chart depicts a rough comparison of subminiature tubes in actual military field installations and of transistors, life-tested in the laboratory. The comparison should be interpreted with these reservations:

1. Field experience for tubes includes various applications, operating conditions and possibly some misapplications, while transistor data is under strict laboratory control.
2. Life test results of both devices are measured in operating hours. It should be noted that high temperature storage conditions (not considered here) can and do seriously affect transistor lifetime figures, even more than operation.

Actual life-test results for both tubes and transistors in general usage and in computer service are shown in Tables 1 and 2.

Table 1 shows observed removal rates for a wide variety of tube types used in an MA-2 Bombing and Navigational system. Transistor failure rates derived from manufacturer's life test data are recorded in Table 2. Again, these data do not include the effect of storage, which in some cases was more severe than actual operation.

To many engineers, transistors seem to be the logical component for computers because of their low power consumption and low impedance circuitry. Table 3 shows recent field failure data for transistors used in computers. As the figures indicate, reliability is excellent.

TABLE 1

Observed Removal Rates for Various Categories of Tubes

Category of Tubes	Removals Per 10 ⁶ Hours
Subminiature Types Except Gas Tubes and Rectifiers	22.1
Miniature Types Except Gas Tubes and Rectifiers	28.7

ARINC Research Corp. Publication No. 110-1-136, Vol. 1 Progress Report No. 2: "Improved Techniques for Design-Stage Prediction"

TABLE 2

Transistors: Failure Rates Derived from Manufacturers' Life Test Data

Transistor Type	Power Level (Watts)	Failure Rate Per Hour, with 95% Confidence Limits (all values x 10 ⁻⁶)		
		Lower Limit	Mean	Upper Limit
"A" Germanium Power	20	56	71	88
"B" Germanium Power	2	24	40	59
"C" Silicon Low-Power	0.2	4	7	12
"D" Germanium Low-Power	0.2	19	21	24

ARINC Research Corp. Publication No. 101-10-137—"Yearly Review of Progress," April 3, 1959.

TABLE 3

Recent Field Failure Data for Semiconductor Devices

Equipment Class	Semiconductor Class	Mean-Time to Failure (Hours)
Computer	Surface Barrier Transistor (Ge)	4,750,000*

Segal R. J., Transac-S-2000, Fifth National Symposium for Reliability and Quality Control, Phila., Pa., January, 1959.

*Converted from Hourly Failure Rate (.0202/thousand hours)

TABLE 4

Reliability of Electron Tubes for Computers

(A) Type 6414 Life Test Results At Or Near Maximum Rating—Plant Life Test.

Failure Rate per cent/1000 hrs.	Life Test Time Hours	Tubes Tested No.	Meantime to Failure Hours
0.11 (inoperatives)	1000	2500	910,000
0.37 (total)**	1000	2500	270,000
0.02 (inoperatives)	5000	450	5,000,000
0.07 (total)	5000	450	1,400,000
0.06 (inoperatives)	10,000	250	1,670,000
0.12 (total)	10,000	250	835,000

*Shorts, opens, air or transconductance slump to less than 10 per cent of bogey are inoperatives.

**Total failures for any reason for any of the tests (or as outside spec. limits).

(B) Type 6414 Customer Life Experience In Computers.

Number of tubes statistically evaluated is 25,000. This is 1 per cent of total usage.

Typical value in per cent/1000 hours during first 10,000 hours of computer use is 0.06. This is removal rate by marginal checking. Only 10 per cent of this 0.06 per cent would have caused an unscheduled shut-down.

Based on removal evaluation, 90 per cent of removals would not have caused a non-scheduled shut-down.

- Mean time to removal is 1,670,000 hours.
- Meantime to failure (non-scheduled shut-down) can be extrapolated to 16,700,000 hours.

That electron tubes also have excellent reliability in computers is demonstrated in Table 4. This is a report of life-testing results of tube type 6414 in

- The manufacturer's plant.
- Actual computer usage.

As can easily be seen, the failure rate in usage is considerably better than in the manufacturer's tests. The factors causing equipment failure in actual use are fewer than in the manufacturer's life test, where as many as five life tests are conducted with up to eight end-points for each test.

In examining these charts it is important to remember that the figures apply to failures, not removals. The removal rate, of course, would be higher.

The evolutionary progress in electron tube reliability for television and for aircraft communications is illustrated in Figures 5 and 6.

To reiterate, it is difficult to make direct reliability comparisons between tubes and transistors. However, it is safe to say that when sound judgment is used in their applications and they are not pushed beyond their limitations, continuous satisfactory performance can be obtained with both devices.

Environment as a factor influencing reliability must be taken into consideration if equipment is to operate outside the region of human comfort. This subject is discussed in the following two sections.

FIGURE 3

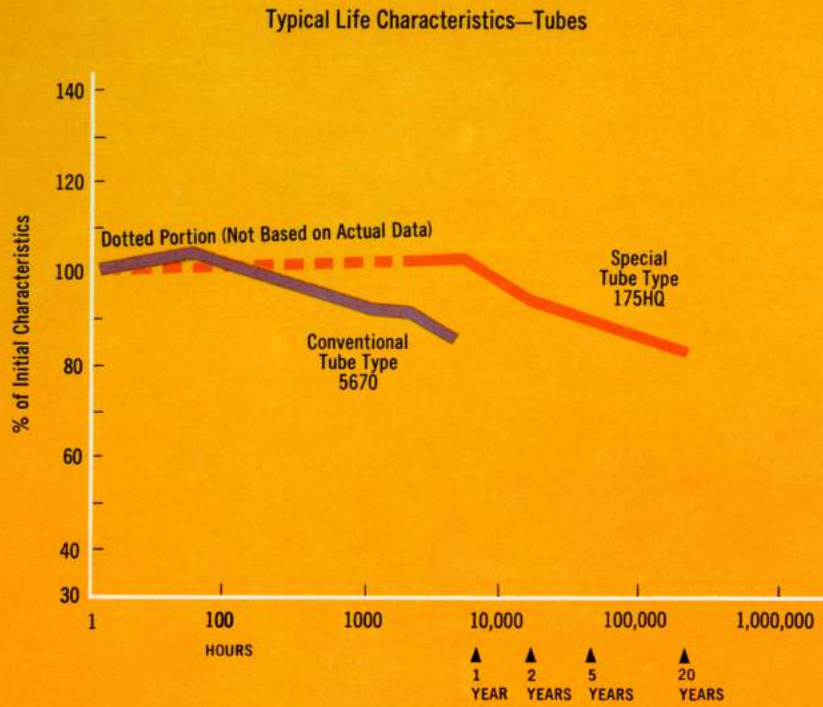
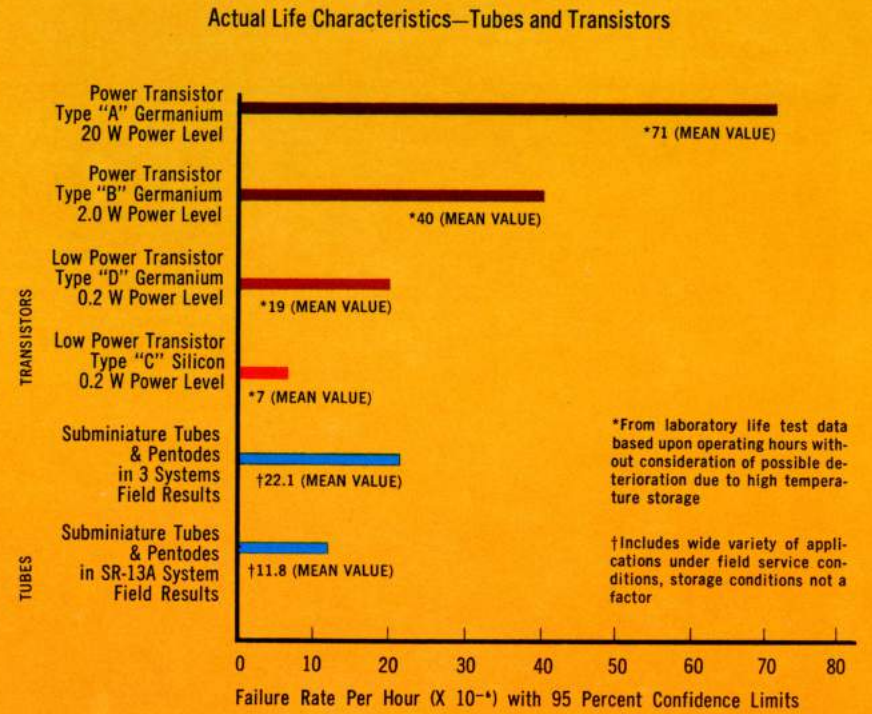


FIGURE 4



From ARINC Research Corp. Publications:
 No. 110-1-136 Vol. 1 Progress Report No. 2 "Improved Techniques for Stage Design Prediction"
 No. 101-10-137 "Yearly Review of Progress" April 3, 1959

FIGURE 5

TV Receiver Tube Reliability Experience Percentage of Survival to 1,000 Hours

MULTIPLE BRANDS—
 10 SETS/BRAND ALL
 SETS RUN AT NORMAL
 LINE VOLTAGES

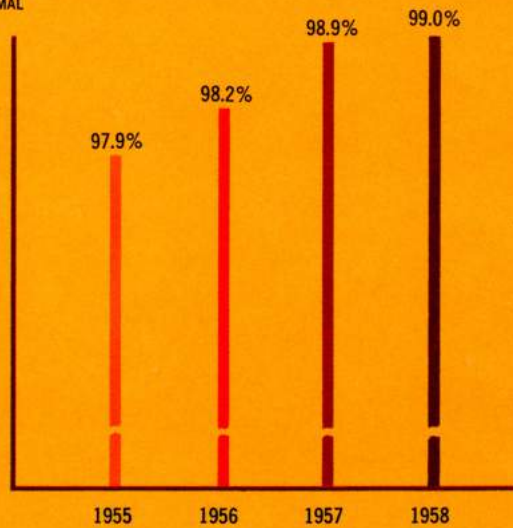
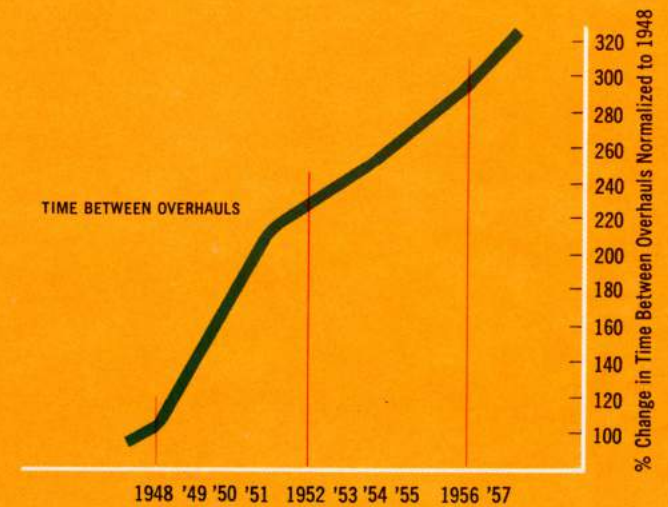
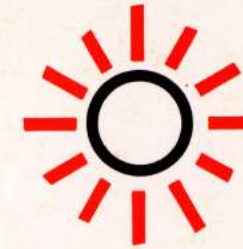


FIGURE 6

DC-6 Commercial Aircraft Improvement in Overhaul Periods with Time



TEMPERATURE CAPABILITY AND STABILITY



Temperatures within the range of human comfort pose no problem for either tubes or transistors. Equipments operating in this temperature range include laboratory computers, hearing aids and entertainment devices. But beyond normal ambient conditions the designer must seriously consider component choice and circuit design.

tube temperature ratings

Electron tubes operate efficiently at high temperatures with practically no change in their characteristics. Glass tubes function effectively under full ratings at temperatures over 200°C , ceramic tubes at more than 400°C . In fact, as a condition of acceptance, certain classes of military tubes specify life testing at bulb temperatures above 225°C for as long as 1,000 hours. It is important to note, however, that the tube continues to function at temperatures in excess of such rated values, although usually at some sacrifice in useful life and reliability. Maximum rated temperature capabilities of reliable military tubes and transistors are compared in Figure 7.

transistor temperature ratings

Transistor operation is restricted to a much narrower temperature range. The limiting physical characteristic of semiconductor devices is the temperature of the junction—which is determined by the combination of electrical operation and environmental temperature. Because of this interrelationship, the maximum dissipation and maximum temperature are described by a derating curve as shown in Figure 7. In this figure, line a-b represents such a derating curve for a typical silicon transistor. Point b at zero collector dissipation is the temperature commonly referred to as the maximum collector temperature. It will be noted that in the case of tubes, maximum rated bulb temperature is at maximum rated plate dissipation (point C_1 and C_2 , Figure 7). Because of this difference in rating systems,

the actual differences in temperature capabilities are even greater than would be implied from the temperature ratings normally published.

tube temperature stability

The electrical characteristics of tubes are virtually unaffected by wide variations in environmental temperature. This is due to the fact that internal parts of the tube normally operate well above ambient temperatures usually encountered. Thus, compensation for variations in environmental temperature is not necessary for proper circuit performance. Temperature effects on tube transconductance for a variety of widely available types are shown in Figure 8. As evidenced by the constancy of the distribution limits shown, these effects are negligible. Limits are essentially the same as the initial specification limits at room temperature.

transistor temperature stability

In contrast, electrical characteristics of transistors are markedly affected by temperature variation. Figure 9 shows the average effects on beta, the current transfer ratio. This is evidenced by the wide variation of the distribution limits. To compensate partially for this instability, a high degree of inverse feedback must be employed, reducing the maximum usable performance attainable per stage. Thus, to perform a given system function, additional transistors and associated circuitry are required.

storage environment factor

Although there are virtually no storage problems with electron tubes, storage temperature can introduce an additional source of deterioration for transistors. As evidence of the importance of this effect and as a control of the device's quality, transistor manufacturers perform life tests under storage conditions.

FIGURE 7

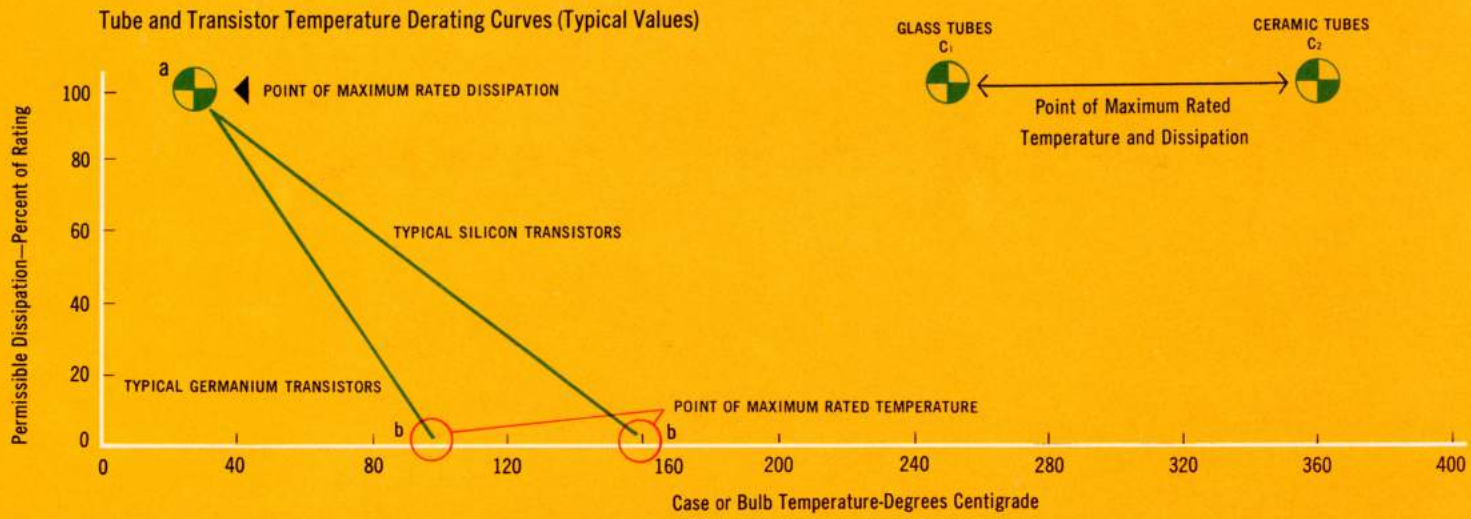


FIGURE 8

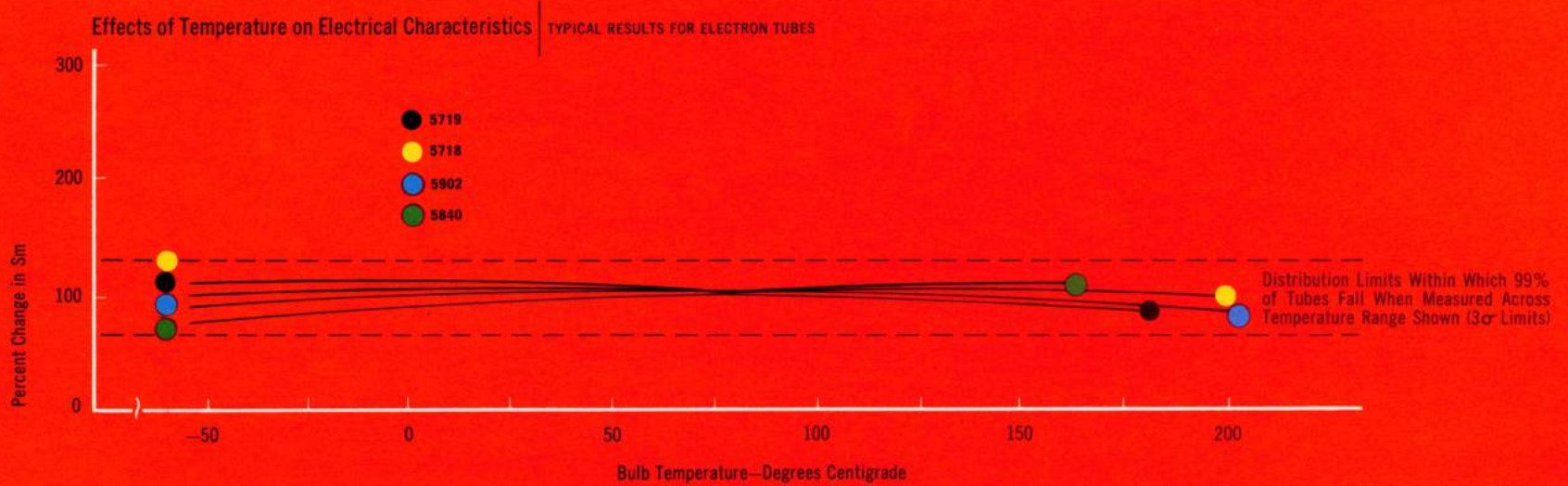
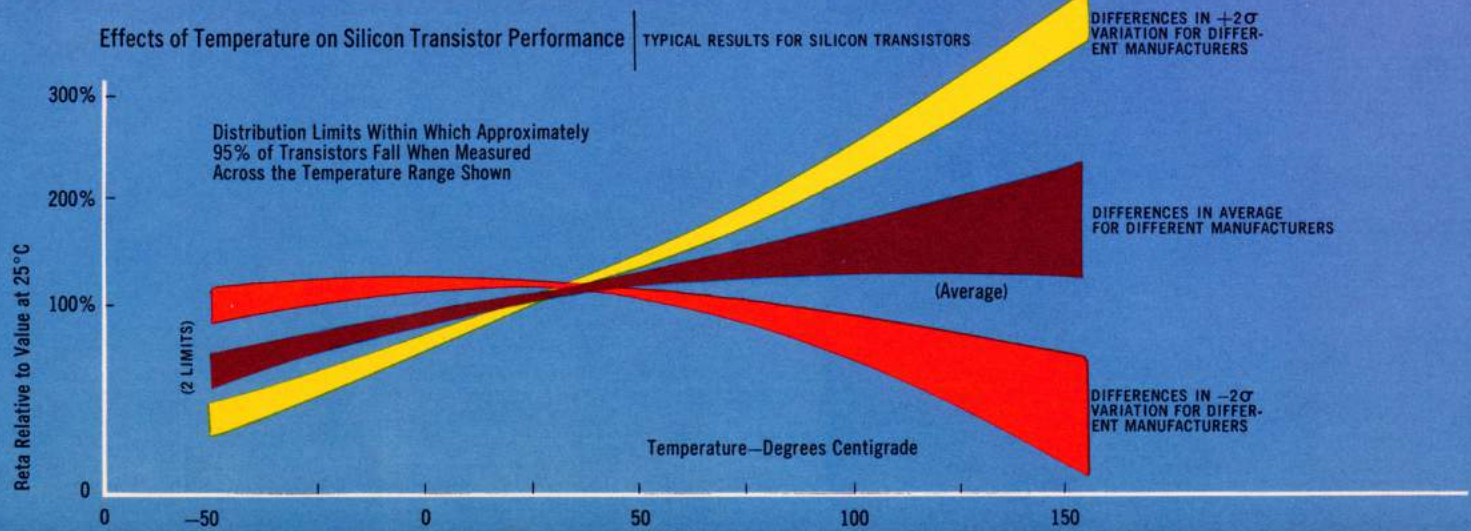
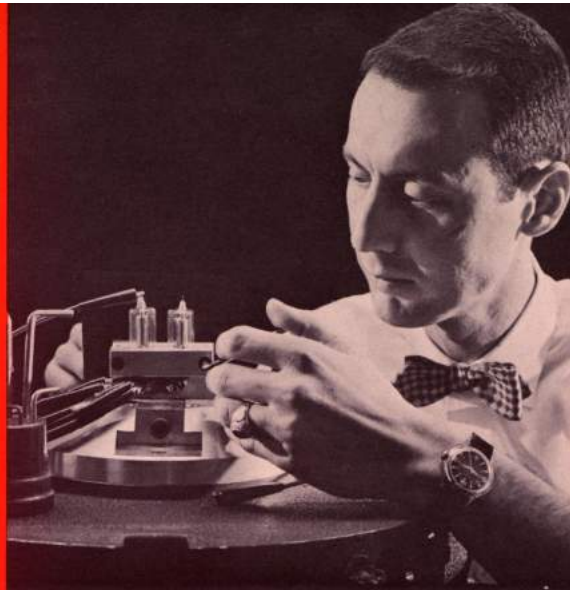


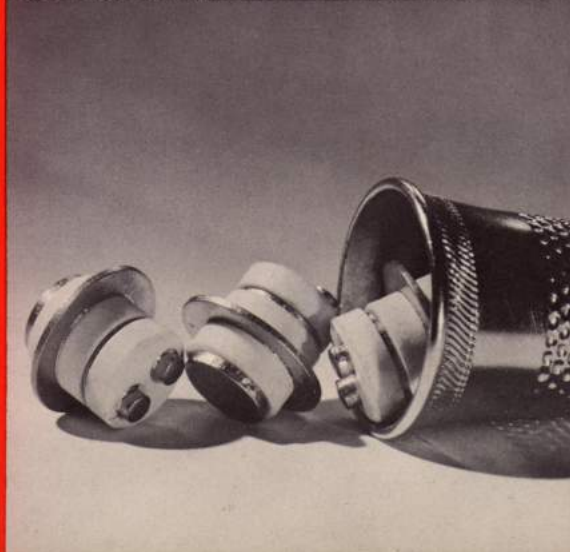
FIGURE 9



Tube vibration test



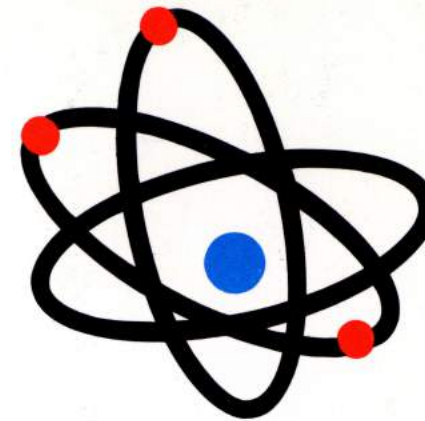
Ceramic tubes



Tube assembly under controlled environmental conditions



ENVIRONMENT



The environments in which an electronic component must operate have a dominant effect upon functional reliability. No matter how desirable its laboratory capabilities, the device will have little field utility if it cannot cope with its conditions of service. Success of equipment design always depends on anticipating these environments and then selecting the components which can best withstand them.

In evaluating tubes and transistors, the important environments to consider are temperature, nuclear radiation, and mechanical conditions (shock, vibration, and spin). *Because of the complexity of the subject of temperature, a separate section, "Temperature Capability and Stability," has been included in this book.*

NUCLEAR RADIATION

Nuclear radiation has only recently evidenced itself as an operating environment for electronic equipment. From a military standpoint, its tremendous importance stems from two considerations: 1) vulnerability of equipment to nuclear blasts, and 2) equipment reliability in or near radiation sources such as fall out, power reactors, or research and measuring devices.

VULNERABILITY

Electronic equipment near nuclear blasts, but outside the area of total destruction, will be subjected to radiation which may be concurrent with, or just prior to, operation. The importance of radiation vulnerability must be evaluated separately for each piece of equipment. In some cases no one knows exactly how vulnerable equipment may be; in others, a "worst probable" basis must be presumed.

Some of the various considerations are:

- Dose (total)
- Dose (rate or flux)
- Energy spectrum
- Type of radiation
- Intervening shielding
- Maintenance problems
- Effect on mission of momentary outage or malfunction

These factors will help determine the intensity and kinds of radiation which the electronic components must withstand. (Gamma radiations and neutrons are the only forms that need be considered here.) After the worst-probable radiation environments are established, the extent of degeneration which may be tolerated in the electronic equipment must be determined. This will strongly influence the choice of components and circuit designs.

nuclear power sources

The effect of radiation on electronic equipment located near nuclear reactors has not yet been of great concern for designers, primarily because of the shielding allowable at existing installations. However, mobile reactors, particularly in aircraft, will probably be shielded very lightly, if at all, because of weight problems. With shielding at an absolute minimum consistent with human safety, fast neutron and gamma radiation will be present in the environs of electronic communication, navigation, and control equipment.

Because nuclear radiation requirements for electronic equipment are of such recent origin, research activity is primarily of a study nature. Appropriate reliability acceptance criteria

are still to be established, and application technology must be evolved. But considerable information already exists concerning the basic capabilities of electron tubes and transistors in radiation environments. There are two factors involved: the rate of exposure and the total dosage. In a sense, the two are interrelated, since if a high rate of exposure persists for a given length of time, maximum dosage will also occur. However, the effects are vastly different.

rate of exposure

High rate of exposure is important because of its momentary effects on the operational capabilities of both tubes and transistors. However, even after an extremely intense rate of exposure the tube's electrical performance will return to normal within microseconds. In contrast, the transistor, which is far more sensitive to radiation effects, may be disabled. There is evidence that when pulse radiation is involved, transistors may be disabled by an amount of radiation far below human tolerance.

Although more information must be accumulated, the capabilities of electron tubes in this respect will permit their use in the following applications:

- Near unshielded nuclear reactors.
- In communications and navigational equipment which must operate at full performance levels immediately after a nuclear blast.
- In electronic equipments which must operate satisfactorily during a nuclear weapons attack.

These capabilities are of great advantage in situations where

even a split-second interruption in operation might abort an entire mission. The transistor is from 1,000 to 100,000 times more sensitive to radiation than most electron tubes. Thus, for transistor recovery, the rate of exposure must be much less than for tubes. Otherwise, a few microseconds exposure will result in some of the effects of total dosage, and the transistor will recover only a small fraction of its original performance or even become completely inoperative. In applications where transistorized equipment may be exposed to radiation, extensive shielding is virtually mandatory.

total dosage effects

The functioning of a semiconductor device depends upon a particular crystalline structure. Exposure to radiation distorts this crystal lattice and alters electrical characteristics. As total dosage increases, a degenerative effect on performance occurs to the eventual point of no utility.

Most component radiation data are expressed in terms of total integrated flux. In available reports of permanent damage to electron tubes, the rate of dosage, rather than the total dose, is believed to be the governing factor. Electron tubes are inherently immune to radiation damage, and extremely high dose rates are required to test tubes to destruction in a reasonable time. Although intense rates of exposure may lead to localized heating of the envelope, there is little or no permanent change in electrical characteristics up to the point that stress patterns induced in the glass cause it to actually fracture. The dosage, or rate of exposure, at which tubes are damaged seems to be largely a function of the boron content of the envelope. There is some variability in radiation tolerance, depending on the

ENVIRONMENT

glass used for a given tube type. Current work with experimental boron-free glass and the development of ceramic structures may both increase the tube's maximum capabilities to the point where even the most severe radiation environments can be readily withstood.

Figure 10 shows typical capabilities of tubes and transistors relative to the tolerance of man. The unit of dose is Roentgen Equivalent Physical (REP). The critical range is indicated by a shading, since a sharp definition of the limit does not exist.

Figure 11, which presents some typical attenuation characteristics of a usual type of shielding for nuclear radiation, suggests the extensive shielding required to lend transistors the immunity of unshielded tubes. A 10-to-1 reduction in exposure from a given weapon requires the shielding shown at the bottom of Figure 11. The polyethylene attenuates the neutron and the lead attenuates the gamma radiation.

Figure 12 indicates typical degradation characteristics for an NPN junction transistor as a function of integrated dose. Performance losses can be partially offset by extremely heavy feedback, but as exposures increase even this technique does not suffice.

Comparable capabilities of electron tubes and various semiconductor devices are shown in Figure 13. For the limits within which semiconductor devices retain any utility at all, the high-frequency transistors have more radiation resistance than the low-frequency units.

MECHANICAL ENVIRONMENTS

Electronic equipment may be subjected to several types of mechanical excitation: shock, vibration, and spin (centrifuge).

Electron tubes were the first control devices called upon to withstand unusual mechanical stresses. Great strides were made as more became known about these conditions and as tube technology advanced. Today, even conventional tubes have demonstrated the ability to withstand any known functional mechanical environment, and new tube structures show promise of adding a liberal safety factor to demonstrated capabilities.

Transistors, because of their small size and mass, have also shown an excellent ability to endure severe mechanical environments. Under extreme conditions their principal problem is separation of the lead from the base metal. This tendency, of course, varies with the individual design.

Limitations of production test equipment prevent control of the ultimate mechanical capabilities of both electron tubes and transistors. In general, conventional specifications establish the same mechanical requirements for both devices, and new developments in tiny low mass electron tubes and transistors are adding further to mechanical tolerance.

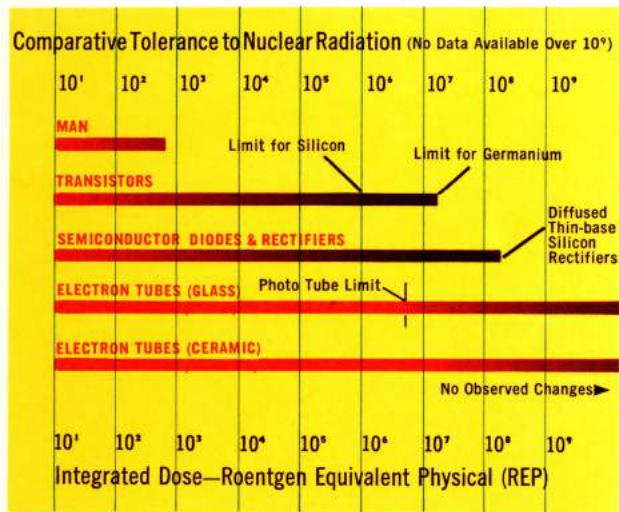


FIGURE 10

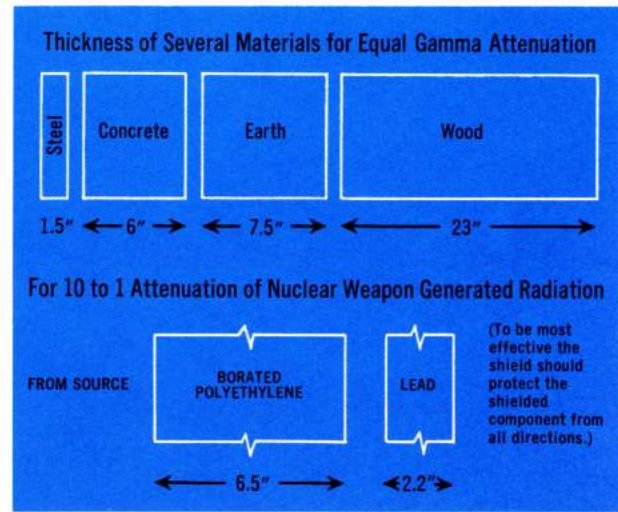


FIGURE 11

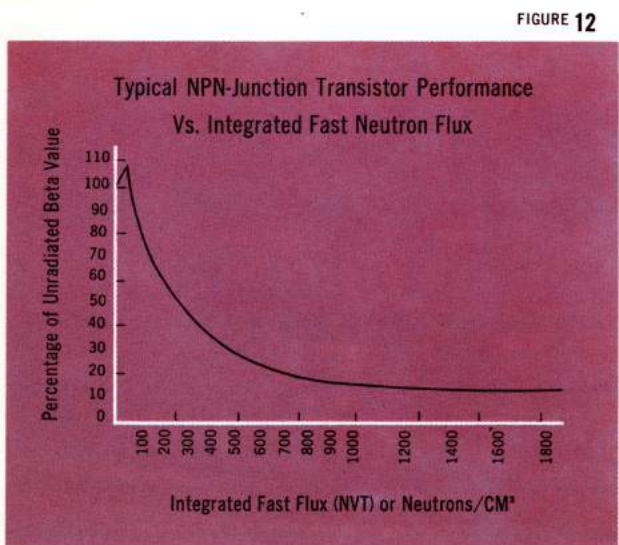


FIGURE 12

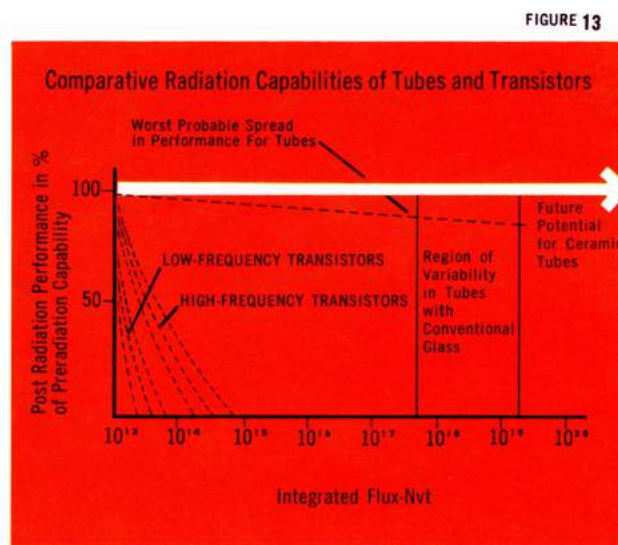
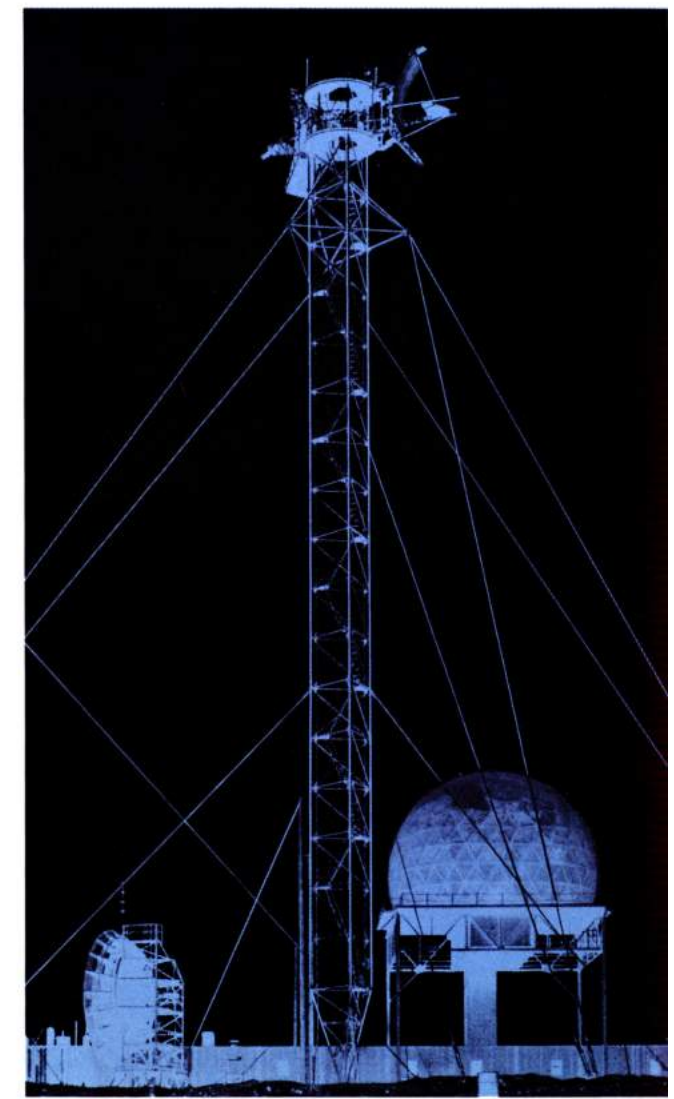


FIGURE 13



SPREAD OF CHARACTERISTICS



Generally, the initial design of an electronic equipment requires the selection of certain key parameters that broadly define operating limits or capabilities. In further refining this broad concept of the design, the engineer evolves detail parameters—explicit physical and electrical limit values for all active elements. It is around these values that he builds his circuits.

Transferring the design from the drawing board to a prototype and finally to a production unit calls for components that will reliably meet the design criteria. Often a design still in process may be influenced by the availability of components having sufficiently narrow spreads of characteristics. These spreads should be narrow enough about the center values (particularly with key parameters) to insure uniform performance and effective maintenance. Unexpected or uncontrolled variations from rated characteristics in a key component can completely destroy the usefulness of an equipment.

In comparing the tendencies of the electron tube and transistor toward an uncontrolled spread of characteristics, there is little doubt that the advantages are almost always with the tube. Published specification limits for several representative tubes and transistors are listed in Table 5. In all instances, transistors show a broader range or variation about the typical, or center, design values than do tubes. The reasons stem from three circumstances—the differences in the inherent character of the two devices, knowledge of the electronic factors at play, and the degree of their control in manufacturing.

electron tubes

The electrical, chemical and physical properties of materials making up the tube and their interaction are comparatively well known. If the tube manufacturer can keep his tolerance within reasonably close ranges, he may safely assume that his production units will have high uniformity.

The close conformity among tubes of a single type is observed through various tests until test specifications are firmly established. The allowable range of variation in a given tube's characteristics is then specified for all manufacturers. Thus, the source of supply for a given tube is of minor importance to the designer specifying it. This interchangeability is valuable to both designers and users. The military user is especially

interested from a logistical standpoint, since replacement tubes may be requisitioned by type number from a broad inventory for all but the most critical types.

transistors

In contrast to the well ordered origin of the tube, transistor production is marked by a number of relatively unknown, and therefore uncontrollable quantities. To a significant extent material properties must be theorized.

The requirement of having to maintain extremely close physical tolerances for the elements that comprise a transistor is a difficult challenge. And since tolerances alone won't give uniformity to the yield, the manufacturer faces another problem—obtaining basic semiconductor materials that will show a reasonably stable response or spread of characteristics for a range of operating conditions.

As a result of these difficulties, transistor producers have adopted 100 per cent sorting, increased automation, and drastic quality control inspections and retesting. Though improvements have been obtained, unit-to-unit uniformity still remains questionable.

Transistor producers have established arbitrary limits on the parameter requirements to be met under test specifications. By setting up a number of specifications to cover various portions of an entire distribution, the producers have been able to make some order out of the original non-uniformity of their production yield. As a result, families of types have been created from what was originally a single component design. The types within a family are identical except for differing limits on one or two specific parameters.

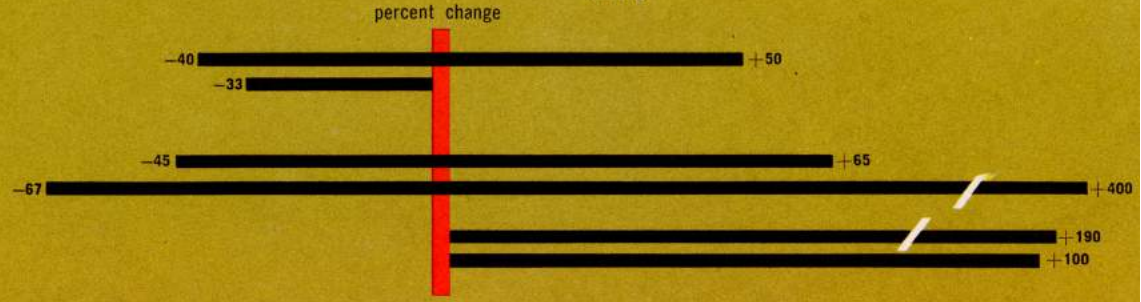
It is apparent that the designer is faced with more than a thousand types when he looks into the possibilities of choosing a transistor for a specific application. If his specification covers a narrow range of characteristic variation, as with servomechanisms, he must be prepared to pay a high price—set by the transistor manufacturer who has to cover the expenses of selecting a small percentage of acceptable units from a large production run. Then, too, the designer using transistors must be willing to forego the interchangeability feature of comparable tubes, which permit specification of a type rather than a single source of supply.

Spread of Characteristics—Tubes and Transistors

TABLE 5

TRANSISTOR TYPE 2N541
LOW LEVEL SIGNAL APPLICATION (200 MW OPERATION)

	min.	typical	max.
Current Gain at 1Kc	80	130	200
Current Gain at 1Mc	10	15	
Power Gain at 1Kc (db)		41	
Noise Figure at 1Kc (db)		19	
Input Impedance (ohms)	30	55	90
Output Admittance (μ mhos)	0.1	0.3	1.5
Voltage Feedback Ratio ($\times 10^{-4}$)		6.0	
Output Capacitance at 1Mc (μ μ f)		7	20
DC Collector Saturation Resistance (ohms)		150	300
Total Dissipation (mw)			200



TUBE TYPE 7025
HIGH-MU TWIN TRIODE

Plate current (ma)	0.85	1.20	1.70
Amplification Factor (μ)	85	100	115
S_m (μ mhos)	1250	1600	2050
Input Capacitance (μ μ f)	1.25	1.6	1.95
Output Capacitance (μ μ f)	0.24	0.34	0.44
Noise Figure (db)			7.6
Plate Dissipation (watt)			1.0



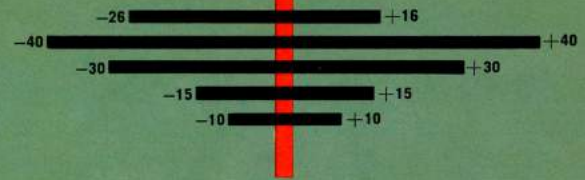
TRANSISTOR TYPE 3N35
TETRODE IF AMPLIFIER

Current Transfer Ratio at 70Mc	1.0	1.6	
Output Capacity at 70Mc (μ μ f)		2	3
Noise Figure at 70Mc (db)		9	14
Power Gain at 70Mc (db)		20	



TUBE TYPE 6CB6
PENTODE

Plate Current (ma)	6.5	9.5	11.0
Screen Current (ma)	1.6	2.8	4.0
S_m (μ mhos)	6000	8500	11000
Input Capacitance (μ μ f)	5.5	6.5	7.5
Output Capacitance (μ μ f)	1.8	2.0	2.2
Noise Figure at 70Mc (db)		6	
Power Gain at 70Mc (db)		25	



TUBE TYPE 6005/6AQ5W
MINIATURE POWER AMPLIFIER (4.5 WATTS)

Plate Current (ma)	33	45	57
Screen current (ma)			7.5
S_m (μ mhos)	3000	4100	5200
Power Output (watts)	3.6	4.5	
Input Capacitance (μ μ f)	6.4		9.6
Output Capacitance (μ μ f)	6.0		11.0



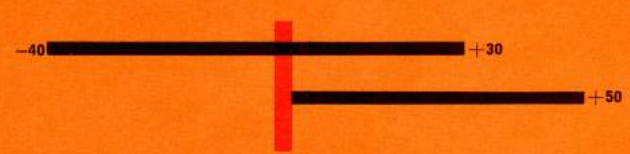
TUBE TYPE 5840
SUBMINIATURE PENTODE

Plate Current (ma)	5.5	7.5	9.5
Screen Current (ma)	1.5		3.3
S_m (μ mhos)	4200	5000	5800
Input Capacitance (μ μ f)	3.5		4.9
Output Capacitance (μ μ f)	2.9		3.9



TRANSISTOR TYPE 2N497
MEDIUM POWER AMPLIFIER (4 WATTS)

Electrical Characteristics at 25°C			
DC Current Gain	12	20	36
DC Input Resistance (ohms)			500
Common Emitter Saturation Resistance (ohms)		20	30
Output Capacitance (μ μ f)		130	
High Frequency Current Gain at 1 Mc		4	



POWER-HANDLING CAPABILITIES



In comparing tubes and transistors for power-handling capabilities, the designer must recognize two fundamental points on which they differ: Their individual operating principles and the limitations that these principles imply. While comparative operating principles are common knowledge among engineers, functional limitations are not so well known—particularly those of the transistor, where much experience is still to be gained.

practical considerations

The established maximum ratings of each device define the practical limitations for satisfactory service. Exceeding these limits, however, can cause trouble.

When voltage and current ratings of electron tubes are exceeded, the results may be gassing, spurious emission, cathode deterioration and insulation breakdown. Although these effects will probably bring about improper circuit operation, the tube itself will usually survive and recover—provided the rating deviation is not exorbitant or applied for too long a period.

Exceeding transistor voltage and current ratings can lead to avalanche breakdown and thermal runaway. Both these effects produce instant and permanent damage.

Of secondary importance are such transient phenomena as arcing in electron tubes and punch-through in transistors. Actually, both effects are usually temporary, merely causing a momentary circuit malfunction with no lasting damage to either device.

Tubes and transistors should be viewed as having their own optimum areas of application. For instance, tubes are clearly preferable where there is a need to operate with high peak-to-peak voltages or transients, high inverse voltages, and high impedances. Transistors are more suitable for applications that involve low voltage supplies and low impedance. A dis-

tinnet advantage of transistors is their ability to operate almost instantly, since no “warm up” time is needed.

efficiency

In a broad sense, the efficiency of either a tube or transistor pertains to how well it performs within its design parameters and how much use it makes of the power derived from its energy source. Any supporting elements or components that dissipate the energy input obviously reduce efficiency.

Generally speaking, since it does not require heater power, the transistor has an advantage over the tube where low power requirements are paramount. Among the more popular applications in this category are the hearing aid, portable radio, output stages of the auto radio, and portable military equipment.

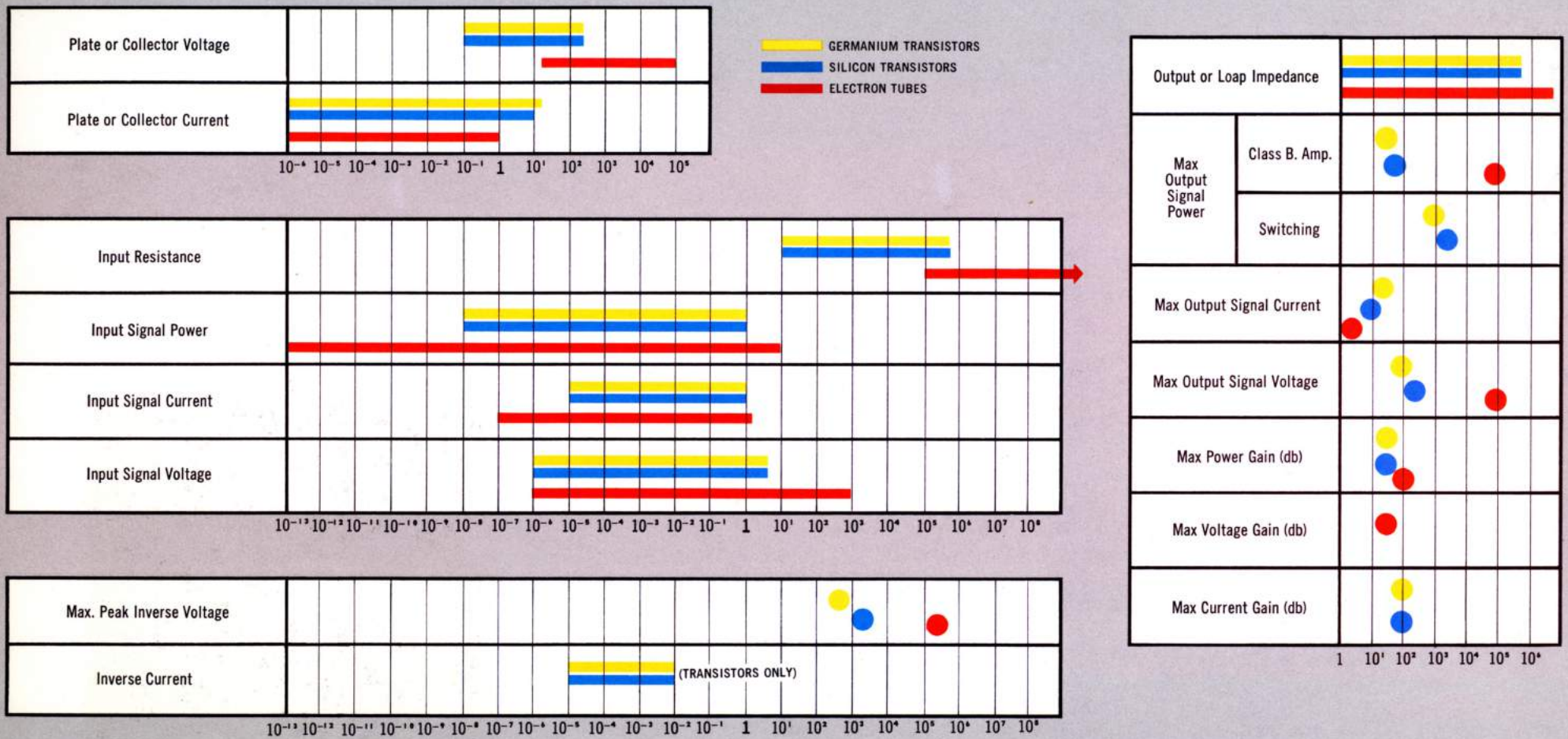
The transistor is also very suitable for power supply use because of its power conversion efficiency at low frequencies. Performance data for transistor inverters show that they reach power output efficiency of up to 95 per cent, including circuit losses.

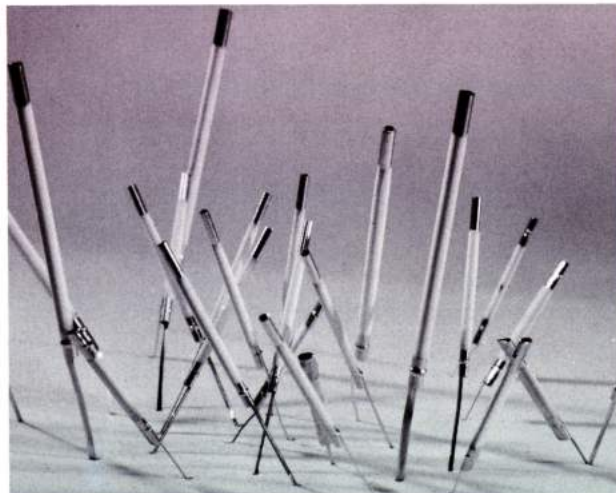
In signal efficiency (the ratio of the output to the signal input), tubes are superior to transistors. Theoretically, in class-A amplifiers tubes have infinite signal efficiency, while the efficiency of transistors is finite. Also, using bias networks in transistor circuits results in signal loss of up to 50 per cent.

Compared for total stand-by power efficiency, or the ratio of the power output versus the amount of stand-by power required, the dividing point is operating frequency. Transistors offer advantages for many small-signal, low-frequency circuit applications. At higher frequencies tubes are clearly more efficient, even taking into account the power their heaters require.

Comparative Satisfactory Electrical Operating Conditions for Electron Tubes and Transistors.

FIGURE 14



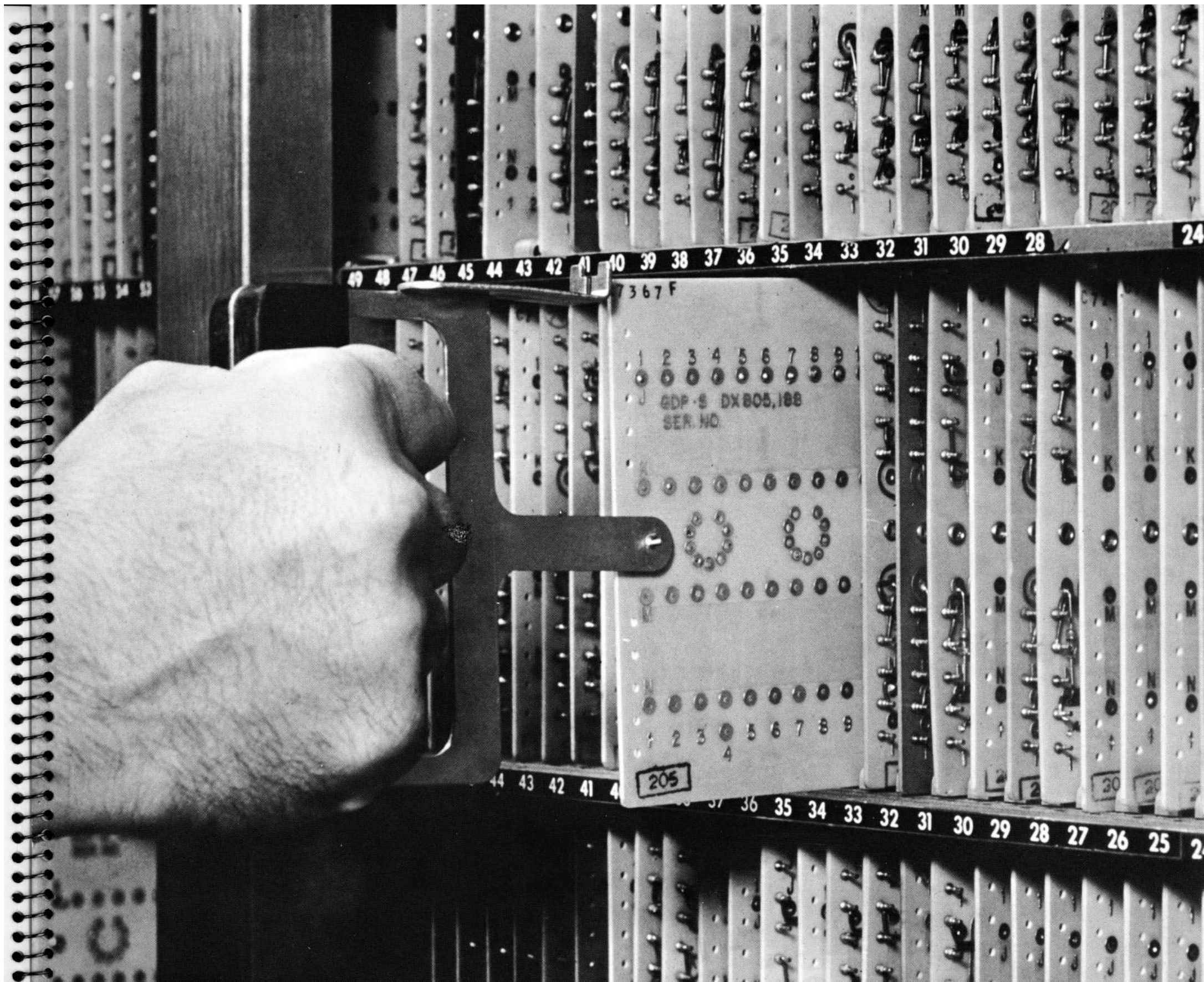


Tube cathodes



Transistor assembly

Transistorized printed circuits in computer processor unit ➤➤➤



INPUT-OUTPUT CAPABILITIES

INPUT-OUTPUT INTERACTION

The problem of input-output interaction is of concern to the design engineer who must consider how much design effort and additional supporting elements are needed to implement a circuit with the desired current flow in the forward direction and with a minimum of reverse gain.

unilateral and bilateral devices

Electron tubes in conventional class-A operation exhibit a high input impedance. Their functioning is unilateral—meaning that changes in the output will not affect the input. At low frequencies the effect of grid-plate capacitance, even in a triode, is relatively small. Thus, feedback is virtually nonexistent. Tetrodes and pentodes inherently extend the frequency range into the UHF region, acting throughout the range as unilateral devices.

Transistors, on the other hand, are inherently bilateral at all frequencies—their input and output impedances are directly related. To minimize this input-output interaction, the designer must convert the bilateral network into a unilateral one, a process termed unilateralization.

A case in point is that of an unneutralized junction transistor stage. Assuming that for an output load it has a parallel resonant circuit, the output load would have an input impedance whose peak coincides with the resonant frequency of the load. If this transistor stage is neutralized, its input impedance can be made substantially independent of frequency.

internal feedback in tubes

Figure 15 is the basic equivalent circuit for a small-signal electron-tube amplifier of the grounded-cathode type. Variations of load impedance (Z_L) have no effect on the input, and vice versa. Just as in the ideal voltage amplifier, the power gain in this circuit is infinite. At the higher frequencies the capacitances must be taken into account, particularly with high impedances. Feedback then will occur between the grid and plate terminals (G and P).

Also, at the very high frequencies, transit-time and lead-inductance effects—the equivalent of a shunt between the G and K terminals—restrict the power gain to a finite value. However, certain negative-grid types of electron tubes are known to amplify at well over 5000 megacycles, and large-signal devices such as oscillators can operate up to 10,000 megacycles.

internal feedback in transistors

The transistor, because of its physical character, is a bilateral device. Actually, it may be regarded as having “internal feedback.” This is demonstrated in the basic equivalent transistor circuit for small-signal amplifiers (Figure 16). For simplicity, the effects of high frequency are neglected.

In this amplifier, current flow in the output influences current flow in the input side. Thus, the input impedance is a function of the load. In the same way, the output impedance, looking back into the transistor with the generator connected, is a function of the generator impedance. These characteristics are extremely significant, since impedance matching from generator to load is of prime importance in a transistor amplifier.

Matching to obtain maximum gain or power output is not always practicable. A good example is the class-A transistor audio power amplifier, in which there is distortion as a result of the nonlinear output characteristics and also clipping in the presence of too large a signal. Although these characteristics are also found in the electron tube, in the transistor the shifting of the quiescent operating point with temperature and nonlinear input impedance poses additional problems for the designer.

Nonlinear input impedance is a major contributor to distortion in transistor amplifiers. Overcoming this problem by resorting to a constant current source to restrict the power gain can be costly. This is true even with the grounded-base connection, since the generator source is provided with a high series resistance. A more successful approach is to select a generator impedance level that minimizes distortion by compensating for both input variations and the non-uniformity of the output

characteristics curve. This rather difficult procedure is probably most frequently used in the output stage of the hybrid automobile receiver.

In the cascade transistor amplifier, interaction between stages assumes critical importance, particularly at the higher frequencies. Referring once more to the equivalent circuit, we find that the generator parameters now are complex values; along with the usual capacitances, the transistor current transfer ratio is a function of frequency. These all vary with temperature at any given frequency. Thus, the transistor's bilateral characteristics and interstage reaction may make tuning difficult, which in turn may affect stability and other output requirements. Neutralizing each stage to get around these problems can be very costly, but is necessary. Another method is to mismatch intentionally, sacrificing gain to minimize parameter variation and interstage coupling effects.

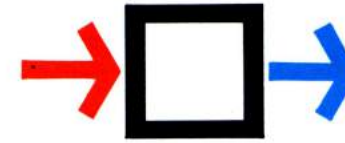
INPUT IMPEDANCE

Though input-output interaction contributes to design complexity, separate consideration is due the problem of input impedance as it influences the choice of tubes or transistors in many amplifier applications. Intrinsicly, the transistor is a current amplifier, the tube a voltage amplifier. Because of its low input impedance, the transistor requires appreciable power to drive it. Since the tube has inherent high input impedance, it needs practically no driving power for class-A operation.

The inherently low input impedance of transistors can be overcome and sometimes even used to good advantage through special design practices. But the extra procedures required to construct high input impedance transistor circuits usually make tubes the better choice.

low-to-high impedance conversion

Many measuring devices call for a high impedance load to prevent overloading. In transistor circuits, high input impedance usually is built in by adding single or cascaded emitter-follower stages. However, there is a limit to the input impedance



that can be obtained by these methods because of the loading effect of the grounded collector. Since the maximum available power gain is limited, voltage gain must be decreased to get high input impedance and low output impedance. Using negative or inverse feedback, the circuit designer can "trade" voltage gain for input impedance.

In transistor d-c amplifiers, getting high input impedance presents even more complex design problems, since the additional requirement of temperature drift compensation enters the picture. The drift in this case stems mainly from the tendency of the collector current to vary with temperature.

Drift effects in the d-c amplifier can be minimized, though not eliminated, by applying bias stabilization or negative feedback. The attendant complexities underline the problem of trying to get high input impedance with transistors.

input comparison

Approximately 1 megohm is the highest input impedance obtainable from a single transistor—the grounded collector configuration with very low gain. In contrast, a single electrometer tube, type 5886, offers an input resistance of 1 million megohms together with a gain of 10.

Multi-element transistor circuits have been developed exhibiting input resistance as high as 1000 megohms (See Figure 17). However, this type of circuit must be reinforced with as many as three or four transistors. Also, liberal use of feedback is required to get the increased input impedance and still have a gain close to unity. A single electrometer tube, the 5886, offers 1000 times more input resistance and ten times as much gain. It has the added advantage of being able to operate with only 12.5 mw at supply voltages of 8.5 and 1.25 volts.

frequency limits

No comparison of transistor input impedance characteristics with those of tubes can neglect their relative response to frequency. The point of major interest to the design engineer is the fact that with increasing frequency the input impedance of

the transistor falls off rapidly. Actually, the transistor ceases to be an active element at frequency levels where the electron tube not only retains effective input impedance but also has considerable gain.

The video IF circuit of a modern TV receiver offers an example of the design problems that arise from low input impedance. To prevent interference patterns from impinging on the desired picture, designers usually provide adjacent channel traps in the video IF stages. This is customarily done for both tube and transistor circuits. Since the tube stages have impedances in the order of several thousands of ohms, relatively simple high-Q traps can be used to attenuate the unwanted signals. However, in transistor receiver circuits, stage input impedances of approximately 100 ohms require the designer to resort to more complex and costly multi-element filters in order to achieve effective interference-trapping.

LINEARITY

In comparing tubes and transistors for their linearity capabilities, the line dividing the two is not always clearly defined. In general, however, tube performance is more linear over a wider range of signal amplitudes.

From the standpoint of inherent capabilities, the tube has a constant and high input impedance at all designed signal levels—no matter what the temperature, supply-voltage or driver-tube variations, or output-load changes may be. Nonlinearity is essentially fixed and predictable, and it can be minimized by proper circuit design.

The transistor presents an altogether different type of performance profile. Its nonlinearity demands special treatment. For instance, a transistor's input impedance might spread in a ratio of more than 2:1 from unit to unit of the same type. Also, an individual unit's input impedance can vary by a like amount over the extremes of ambient temperature and with variations of load impedance.

Where linearity is a prime requirement, the designer must

recognize what measures are needed to get performance out of transistors that is comparable to tubes. Some of the most important are outlined below.

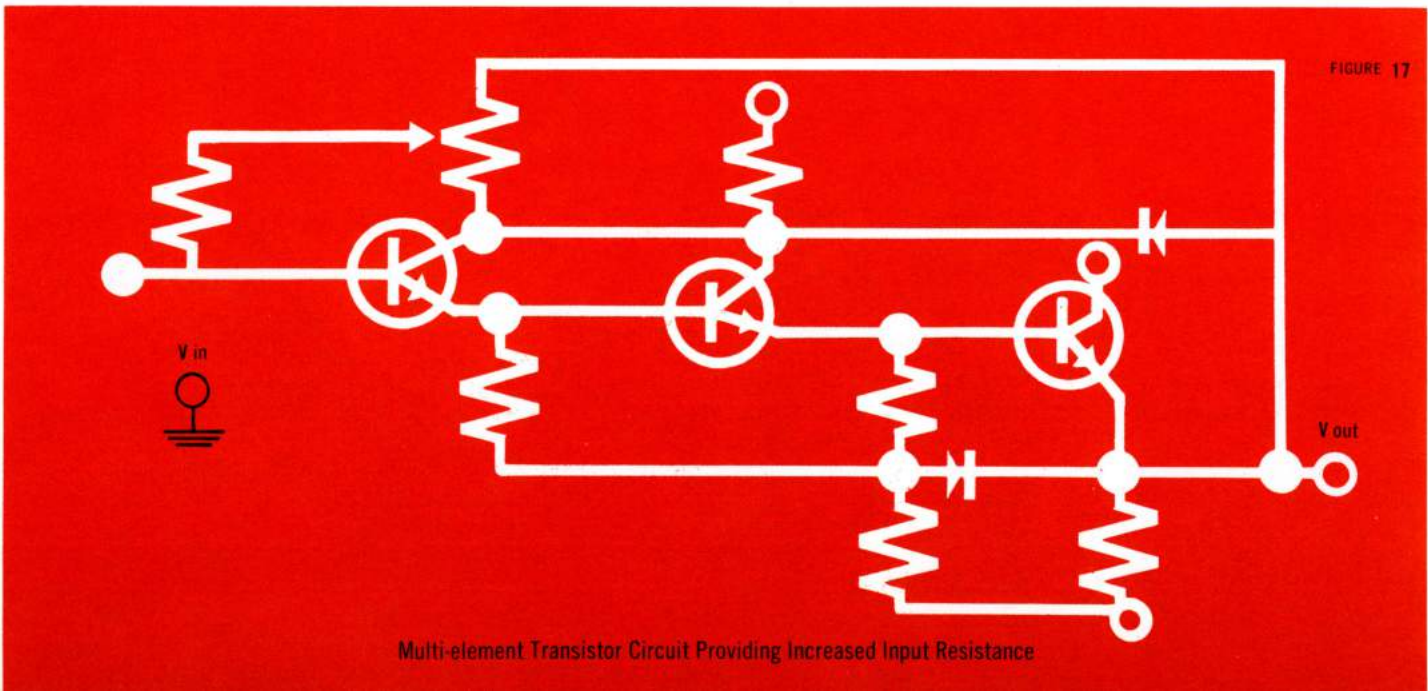
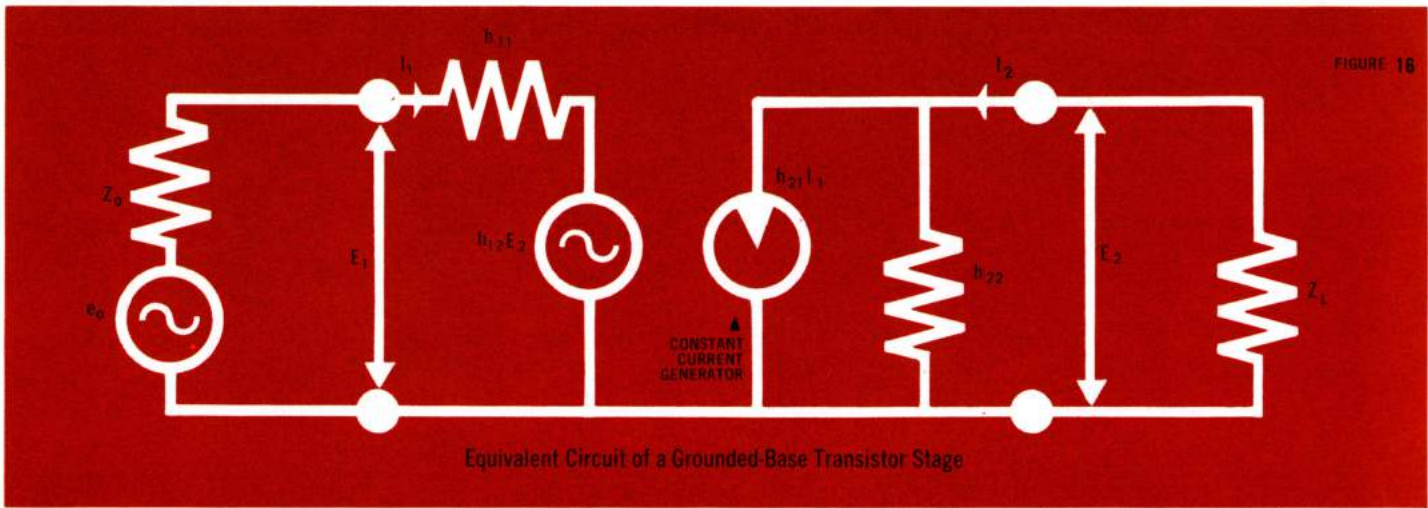
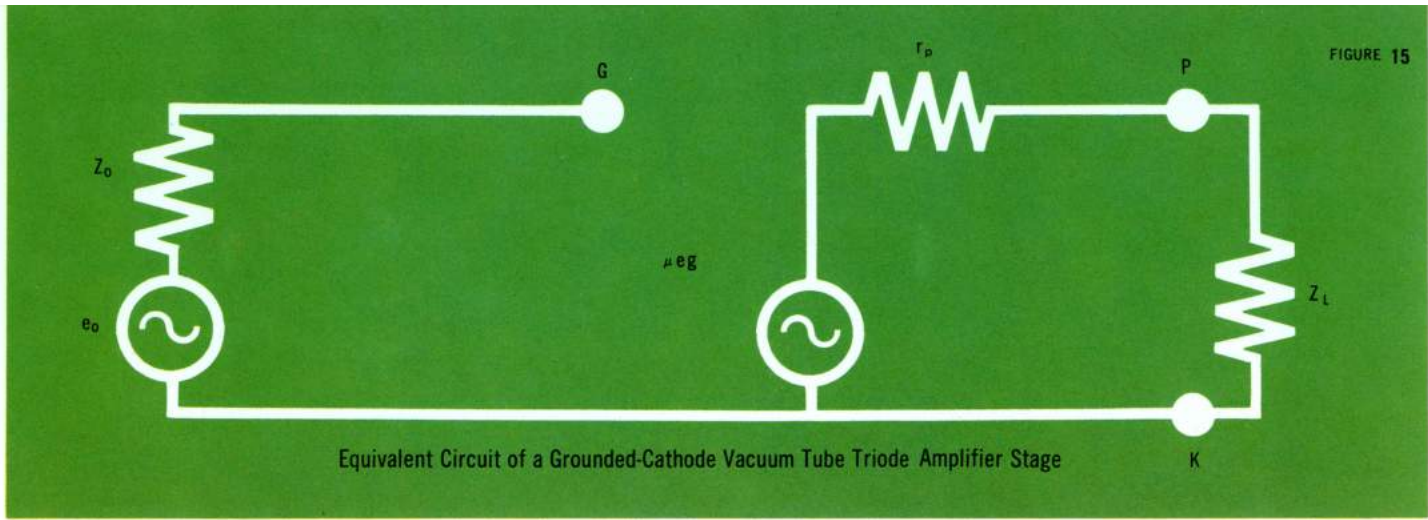
A comparison of alloy-junction transistors and remote-cutoff pentodes indicates that for low signal levels—those associated with one per cent of cross-modulation—the transistor can be made to give linear output resembling that of a tube. However, the low bias voltage on the transistor allows only a small signal amplitude to pass without clipping.

Interference signals that produce clipping lead to severe distortion. Generally, receiving tubes with remote control characteristics can handle signals at least an order of magnitude greater than transistors before distortion occurs.

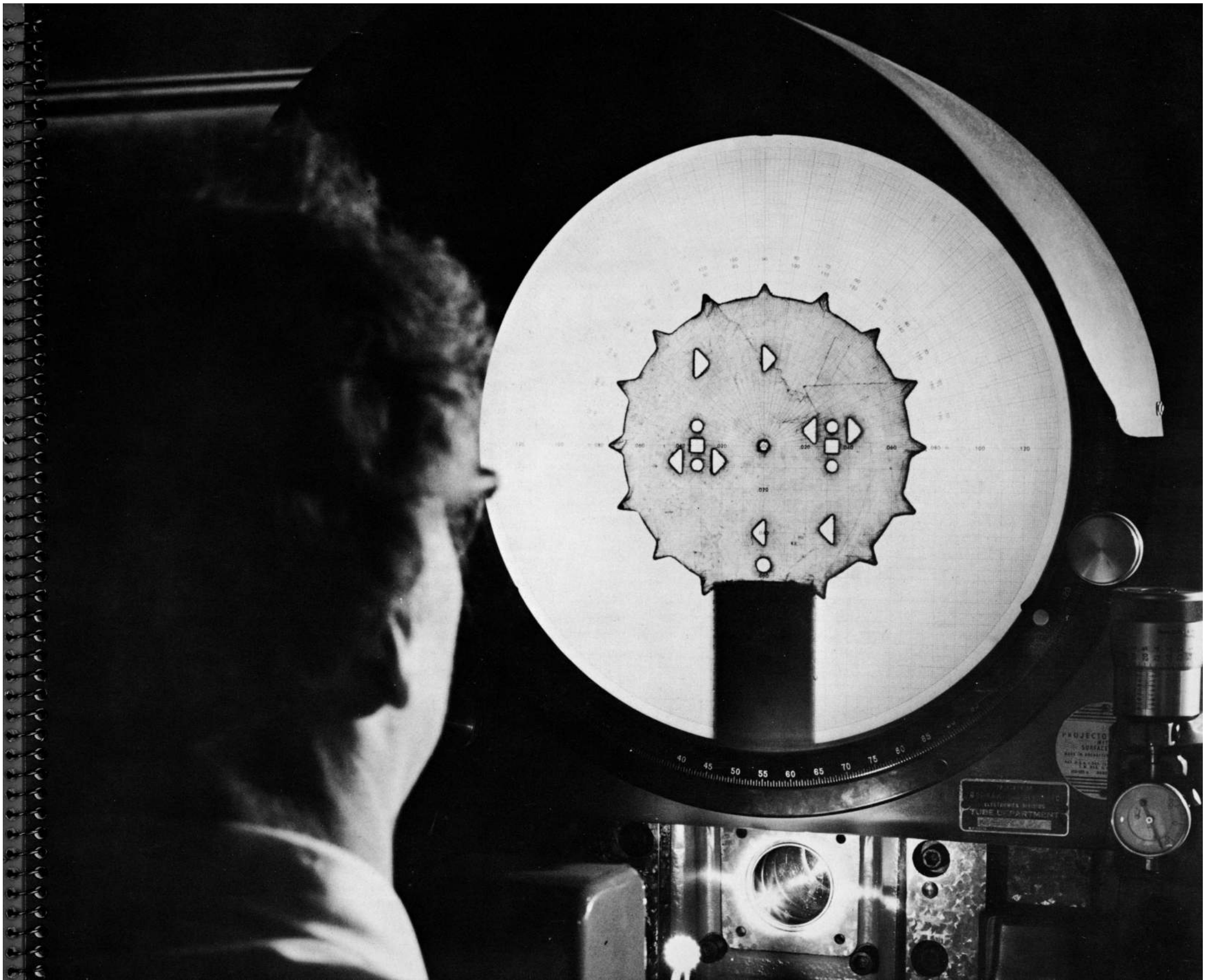
If he is to bring the transistor's power output to a reasonable level, the circuit designer must select the proper circuit configuration. This often involves a significant added expense. Usually he uses the common-emitter arrangement for the output stage of transistor amplifiers. Though common-base d-c biasing is more stable, and though both common-base and common-collector give better linearity, common-emitter biasing can give highest power output while offering advantageous impedance levels.

Distortion values approaching the low levels for electron tubes can be designed into transistor amplifiers by using push-pull class-A output stages. Such stages have a theoretical maximum efficiency of only 50 per cent, so the quiescent energy dissipation must be at least twice as great as the desired maximum output power.

A unique method for minimizing distortion is the use of a "complementary symmetry" circuit. It eliminates transformers while keeping the advantages of push-pull circuitry, and it entails using transistors of opposite polarity (PNP and NPN). Distortion from even harmonics is then cancelled and no direct current flows in the load. Further, this circuit obviates an input transformer or phase inverter.



Precision check of tube mica tolerances ➡



HIGH-FREQUENCY CAPABILITIES

The factors which limit the high-frequency capabilities of the tube and the transistor vary widely. The fundamental limit in the electron tube is the transit time loading between the grid and the cathode. This effect, similar to that of a pure resistance, changes inversely with the square of the operating frequency. To reduce this loading, the grid-to-cathode distance must be minimized.

The transistor's high-frequency capability is affected by the transit time of the carriers injected from emitter to collector, collector capacitance, and base resistance. For the best high frequency performance, all three factors must be minimized.

tube performance

Typical spacing in high frequency tubes is approximately one- to two-thousandths of an inch. Smaller distances do not reduce the transit time loading substantially because of the position of the electron space charge around the cathode.

Today's production techniques make this optimum spacing economically feasible; the use of frame grids, planar structures, cylindrical symmetry, and precision jigs are common examples. The other basic limit to the high-frequency operation of electron tubes is capacitance, which must be kept to a minimum for best results.

Since both transit time loading and capacitance increase with the size of tube elements, tubes are being made smaller and smaller. Tube designers throughout the past decade have boosted high performance into the kilo-megacycle range. The nuvistor and the small ceramic triodes are dramatic evidence of this trend. The practical limit of such miniaturization is maximum cathode current density, commensurate with long life and adequate heat dissipation.

transistor performance

In the junction transistor, the movement of injected carriers in the base region determines the transit time. This diffusion is a

random process and can be accelerated by adding a strong field, or by reducing the base thickness.

Collector capacitance can be minimized by using very small structures and by controlling impurities in the collector. Controlling impurities can also cut down base resistance. These modifications have made possible drift transistors, PNIP structures, micro-alloyed diffused-base transistors, and "mesa" types of diffused base transistors.

But these parameters cannot be improved indefinitely. A collector that is too small, for example, will not dissipate heat adequately and can thus reduce the transistor's power output. Also, the base thickness is limited by "punch through" that can result when higher voltages are applied to speed up diffusion.

For similar high-frequency performance, the transistor must have much smaller spacings and smaller electrode dimensions than an electron tube because of the high dielectric constant (high capacitance) and low charge mobility in solids as compared to a vacuum space. The dimensions and spacings of active parts in a modern micro-alloy diffused transistor having a frequency cutoff of 600 megacycles are approximately 1/20th those of the active parts of electron tubes designed for efficient operation at frequencies up to 2000 megacycles. Thus, the manufacture of transistors for high-frequency applications is far more critical.

power and gain at high frequencies

The present development of tubes and transistors is summarized in Figure 18. From this it is clear that where high power at the higher frequencies is required, the electron tube has a distinct advantage.

A comparison of the relative power gain of the two devices is given in Figure 19. Here again, where higher power gain at higher frequencies is called for, the tube will give better performance. These curves represent the maximum available power gains under matched conditions. However, under broad-



band conditions at lower frequencies, the transistor, with its lower inherent impedance, may provide more gain per stage than the tube.

the application determines the choice

The basic frequency capability differences between the two devices can be shown by their use in television tuners. For example, a tuner designed to use three high frequency transistors has a power gain equal to, and sometimes greater than, that of a two-tube (pentode, triode-pentode) tuner.

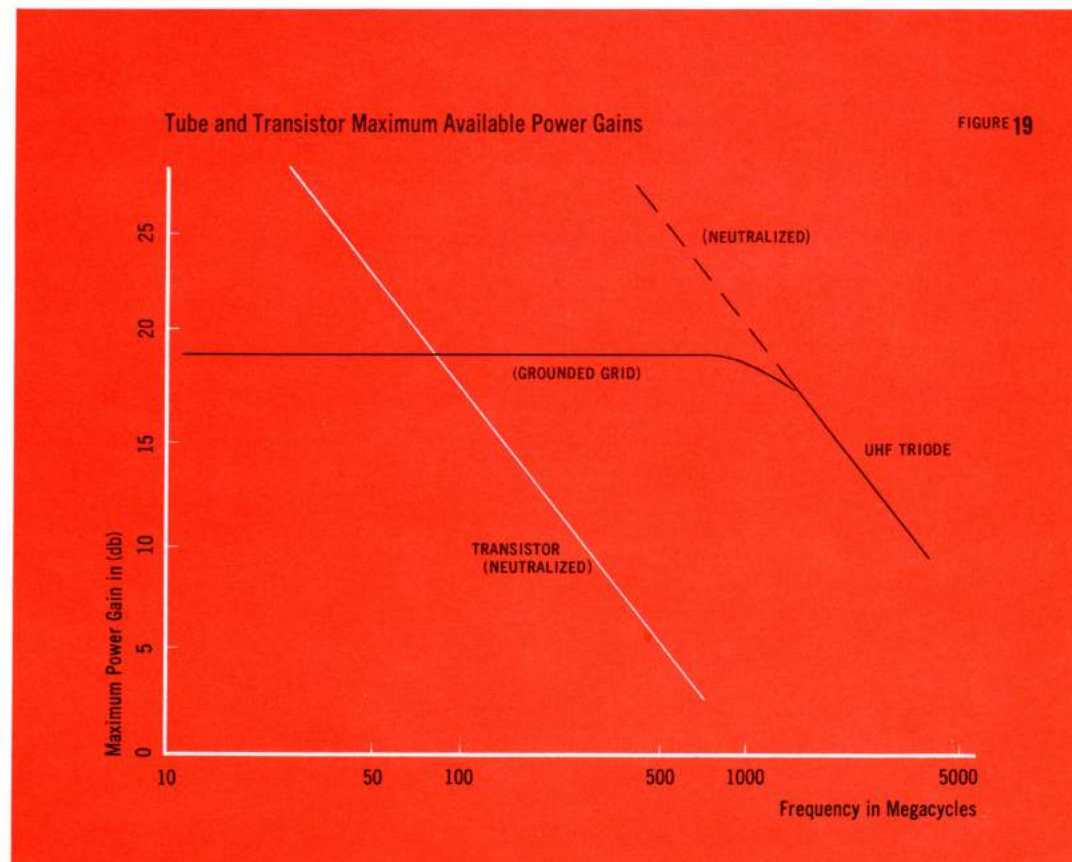
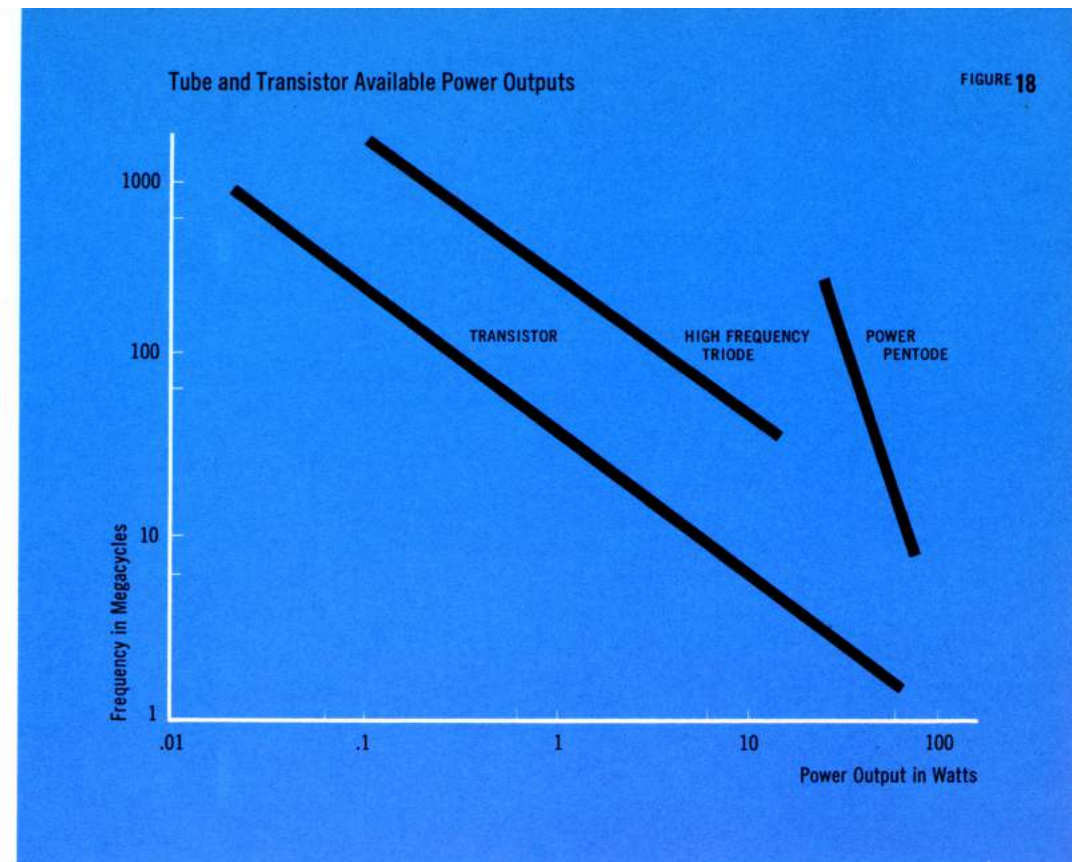
The noise performances of tube and transistor tuners vary considerably. The section on Noise Performance develops in detail the subject of available noise figures.

Both devices can be supplemented with automatic gain control, though the transistor cannot be "cut off" in the same sense as can the electron tube. However, a transistor tuner does not have the "tilt" problems often occurring with a tube tuner.

Because of its reduced selectivity under strong signal conditions, the transistor tuner is more susceptible to modulation distortion. This distortion is also more severe in the transistor tuner because of its inherent nonlinearity under large-signal conditions. In the tube tuner, the use of remote-cutoff grids to control selectivity under large-signal conditions has proved the best solution to the problem of distortion. There are usually no selectivity problems with either the transistor or tube type tuner.

Since the transistor does not need heater circuitry, as does the tube tuner, the circuitry cost of the transistor tuner would appear to be less. But the high cost of the VHF transistor, plus the need to select units for each function within the tuner, makes the over-all cost higher than if tubes were used.

The transistor tuner represents a reduction in both size and power requirements. However, the advent of new tubes, such as the nuvistor, will contribute much toward meeting miniaturization requirements.



NOISE CONSIDERATIONS

Noise is another important characteristic that influences the designer's evaluation of the comparative performance of electronic devices. Since noise limits ultimate sensitivity, it is a critical factor, if not a disabling one, in many circuit applications. High-gain microphone stages, low-level instrumentation inputs, and sensitive r-f amplifiers are examples of such applications.

noise sources

The noise generated within tubes and transistors is caused by various phenomena, related for the most part only in frequency. Four of the most important types of noise, common to both devices, are known as:

- Inverse-frequency noise
- Frequency-independent noise
- High frequency noise
- Microphonics and hum

In the transistor, the inverse-frequency noise is caused by both leakage and surface conditions. The same type of noise in the electron tube is generated by the "flicker" effect due to low-frequency fluctuations in emission current.

Frequency-independent noise—also referred to as white, shot, thermal or Johnson noise—predominates at frequencies where the lowest over-all noise figures for both devices are obtained. In the transistor, this noise is associated with bulk leakages and with diffusion and recombination fluctuations. Similar noise in tubes may be produced by bulk leakages of the supporting structures, shot noise caused by the plate and screen-grid currents, and, at times, by primary and secondary electrons liberated from the screen-grid and plate structures.

Probably the most significant noise source is the high frequency component that increases with operating frequency. In the transistor, this usually has to do with the diffusion process in the base region and also with recombination fluctuations. Since finite time intervals are related to these processes, transistor noise output changes with frequency.

High frequency noise in the tube is affected by the transit time between the grid and the cathode and thus varies with frequency. The effect of this characteristic on the noise figure shows up at frequencies where the tube's noise output comes close to that caused by thermal and shot noise.

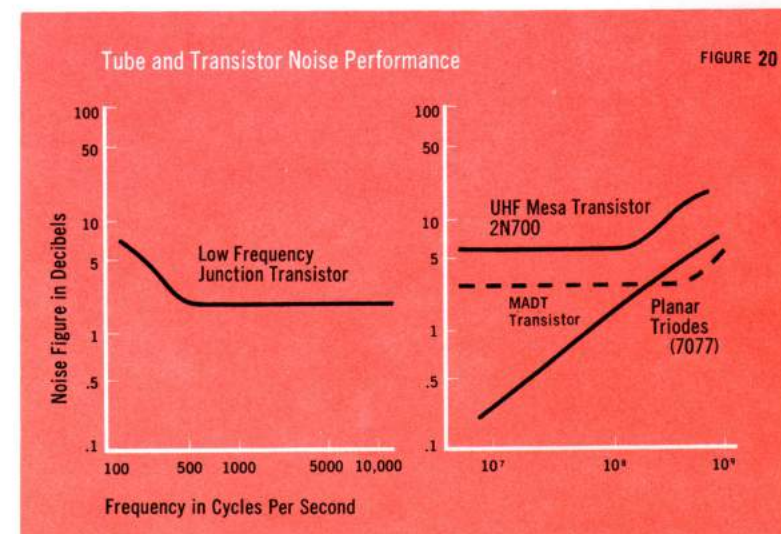
Microphonics and hum occur in tubes in the low frequency range. Although these two characteristics are being steadily reduced, it should be recognized that the problem is nonexistent in transistors.

noise figure comparison

Noise figures for both devices are compared in Figure 20. The relatively high noise figures for transistors in the mid-frequency range indicate that the diffusion and recombination processes generate much more noise than the shot and thermal noises in either device. By selecting special transistors, these noise sources can be cut down so that they are not troublesome in general audio usage. However, in low-level signal applications, the fundamental sensitivity of the device is limited owing to low frequency noises that develop within the audio range.

Lower noise figures can be achieved with tubes; in fact, the mid-frequency noise figures are much lower than those of transistors (see Figure 20). Also, low-frequency noise in tubes usually is not apparent in the audio range. Actually, certain types of tubes can amplify signals in the microvolt range at frequencies of less than one cycle per second without introducing excessive masking noises.

Another reason for the low noise characteristics of the tube is the fact, sometimes overlooked, that the space charge generated by the hot cathode provides the best single source of thermal noise reduction found within the tube.

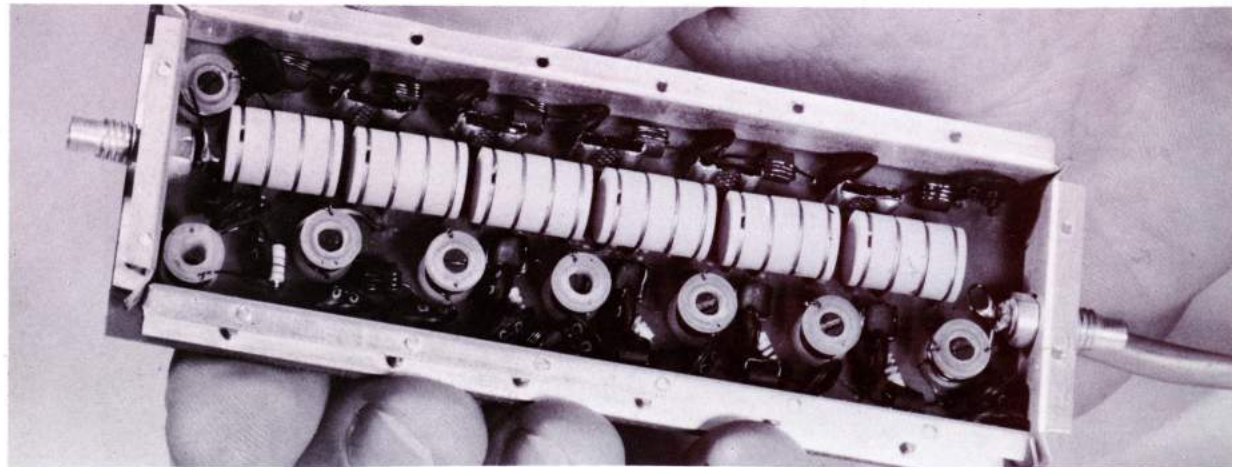


SIZE AND WEIGHT

Present day developments in electronics for missiles, aircraft, communications and entertainment equipments are bringing about increasing demands for miniaturization. This effort to pare down size and weight has, in turn, introduced new problems of cost and possible compromises in circuit design and quality.

The most publicized factor in the miniaturization of electronic equipment is the transistor. It has made possible many significant innovations in various types of products: Less obtrusive hearing aids, more compact portable transceivers for military communications, and desk size computers are but a few examples.

There is no doubt that where small size and low weight are the major considerations, the transistor has a distinct advantage over the electron tube. There are exceptions, however. In some applications of the transistor (especially the smaller versions), the heat sink required to counteract ambient temperature limitations may be larger than the transistor itself and perhaps even larger than a tube of similar output. Similarly, the use of transistors in high-performance amplifier designs usually calls for additional circuitry and stages to get the negative feedback needed for stability, uniformity and interchangeability. In these cases, a larger number of transistors than tubes may be required to perform a given function, and the equipment's size and weight may actually be increased. In certain military equipments, tube versions are smaller than those using transistors because tubes do not require the bulky filter components which semiconductor devices use to compensate for their high-current, low-impedance characteristics.

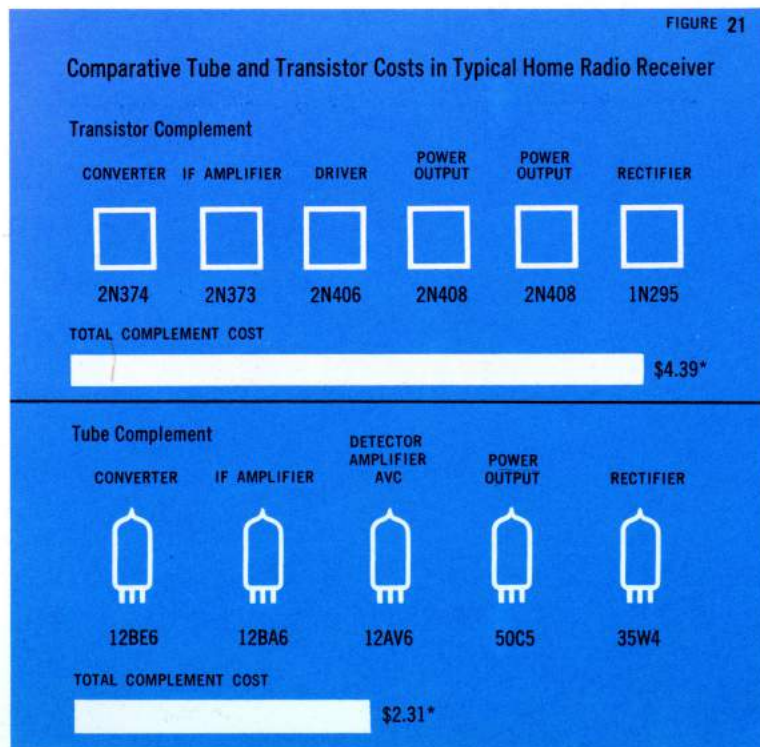


COSTS

The economies of miniaturization point up the ironic fact that "the smallest package often carries the biggest price tag."

New inventions usually follow a certain cost pattern. That is, the price is high at first; then, as consumption increases and the rate of production rejects lessens, costs drop proportionately. Today, the transistor is still priced higher than the tube, but lower than when it appeared on the market in 1952. As it continues to develop, prices will gradually come down still further.

For the present, however, the equipment manufacturer who uses transistors has to face the fact that his initial costs will be more than if he had used tubes. An average home radio receiver serves as an illustration. Figure 21 lists tube and transistor complements that might be used and the total costs of each to the equipment manufacturer.



*Based on Prices Prevailing September 30, 1959

This comparison indicates an approximate 2 to 1 cost ratio in favor of tubes. Of course, this ratio is not necessarily valid for other types of equipment—nor are all the factors affecting the total cost of the equipment itself included. For instance, in the radio example cited, the transistor unit calls for two more transformers, more resistors and more capacitors. On the other hand, the transistor unit avoids the electrolytic capacitors and the large resistor required in the tube power supply circuit. With transistors, less expensive capacitors having lower voltage ratings can generally be used.

From the over-all standpoint of the equipment manufacturer, still more factors must be considered. These include comparative circuit engineering costs, factory line rejects, and warranty replacement costs.

military equipment costs

In military equipments, the higher cost of transistor complements is more pronounced.

Military type electron tubes generally cost about three times as much as entertainment types because of additional specifications and the degree of manufacturing precision required. But this ratio is much higher for transistors. For many military applications, wide temperature environments demand the use of today's more expensive silicon transistors. In addition, these applications require far greater manufacturing precision and even more specification criteria. Finally, the lower performance per unit obtained with silicon transistors creates a demand for more units and added passive components. All these factors combine to make the cost ratio of transistor to tube components many times higher than the 2 to 1 relationship shown for consumer products.

The semiconductor industry has predicted significant price reductions for the future. However, many complex technical and commercial factors make it exceedingly difficult to accurately forecast comparative over-all equipments costs. But for the next several years, at least, tubed equipment will remain much less expensive than transistorized equipment.



LOGISTICS



Logistics, a military science by definition, was described by the late Secretary of Defense James Forrestal as "...the process of providing what is needed when it is needed where it is needed. It embraces the supply and distribution of men and materials. It involves forecasting requirements. It is the scheduling, production, assembly, storage, distribution, maintenance, repair and replenishment of equipment..."

In the electronics industry, logistical considerations fall into these categories:

1. MULTIPLE SOURCES OF SUPPLY

This is usually considered necessary in order to protect against interruptions in the flow of the product. A single source of supply might have to suspend deliveries because of strikes, production problems, disasters, or enemy military action.

2. INTERCHANGEABILITY AND/OR UNIFORMITY

A given tube or transistor should be interchangeable with any other of the same type designation, without the necessity of selection between manufacturers or between individual units. "Equivalent" types should also be interchangeable without selection to avoid constant design changes during production and to insure continued full-scale utility of equipments after repair.

3. SERVICEABILITY

Maintenance must be simple to insure maximum utilization of equipments in field service and to minimize service costs. If it is difficult, then new design techniques, such as modular construction, should be employed to ease servicing problems.

4. AVAILABILITY

If components are not available in sufficient quantity, equipment production can be seriously restricted.

Also, an early obsolescence of certain tube or transistor types will cause a lack of replacement parts for equipments in field service.

5. STORAGE

Unless special provisions are made, components affected by storage conditions become unserviceable.

standardization and interchangeability

The most important factor affecting a logistical comparison of tubes and transistors is standardization, and here, tubes have a definite advantage. Standardization of tubes is now at the point where a specific tube type can be obtained from several sources; no sacrifice in parameter values need be made, since tubes carrying the same type designation are interchangeable. Transistor standardization still is in its initial phase, although definitions and test methods for both semiconductor diodes and transistors are being prepared.

Several manufacturers of diodes and transistors publish interchangeability charts to specify which of their type numbers can be substituted for those made by competitors. This type of interchangeability, however, is generally limited to non-critical applications.

The military is hardest hit by the problems of transistor interchangeability; large quantities of various types must now be inventoried, stocked, requisitioned and transported to key areas. Another serious problem for military personnel is the fact that many early transistor types have been discontinued. Merely substituting new ones is not in accordance with military procedure; every new transistor must be completely evaluated and tested before it can be deemed acceptable.

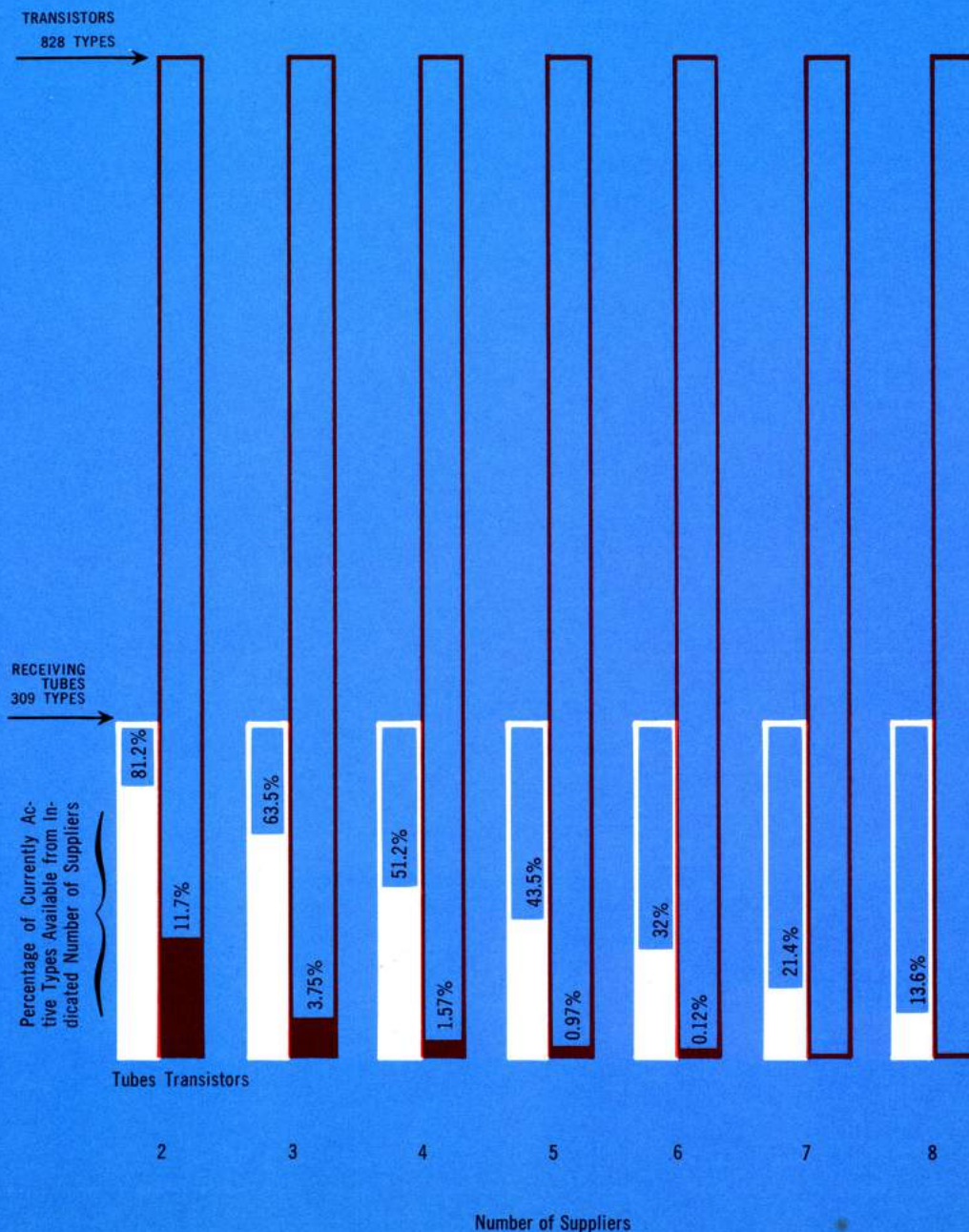
tabulated comparisons

The adjacent chart points up some of the basic logistical factors which exist at present. A detailed summary of the availability of tubes and transistors from multiple sources is provided in Figure 22.

Sources of Supply—Tubes / Transistors

Note:
 Transistor sources of supply may not be as severe as portrayed. Possibilities for "interchangeability" exist, but would be very much dependent upon individual types under consideration and the circuit application involved. Inclusion here would be purely conjectural.

Logistical Comparisons	
STATUS OF TUBES	STATUS OF TRANSISTORS
<p>Multiple Sources of Supply Almost all types available from two or more sources.</p>	<p>Multiple Sources of Supply Less than 12% of all types available from two or more sources.</p>
<p>Interchangeability and/or Uniformity Tube specifications are standardized. Most applications use stock items without selection. Easily interchangeable between manufacturers and from unit to unit.</p>	<p>Interchangeability and/or Uniformity Effective standardization just beginning. Interchangeability of a specific type, even among several manufacturers, is limited because of divergence in controlled parameters.</p>
<p>Serviceability Maintenance of tube equipments comparatively simple. Tubes are generally removed easily from equipment for testing and not readily damaged from inadvertent application of external voltages or leakage currents.</p>	<p>Serviceability Servicing difficult because units are generally wired into compact circuits. Prone to heat damage from soldering irons and electrical damage from test equipment or leakage currents.</p>
<p>Availability Most tube types are available for replacement purposes.</p>	<p>Availability Rapid development has made early types obsolete, therefore generally unavailable.</p>
<p>Storage Not degraded by high temperature storage conditions.</p>	<p>Storage Degraded by high temperature storage conditions.</p>



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