INCREASING TUBE RELIABILITY IN INDUSTRIAL CIRCUITS

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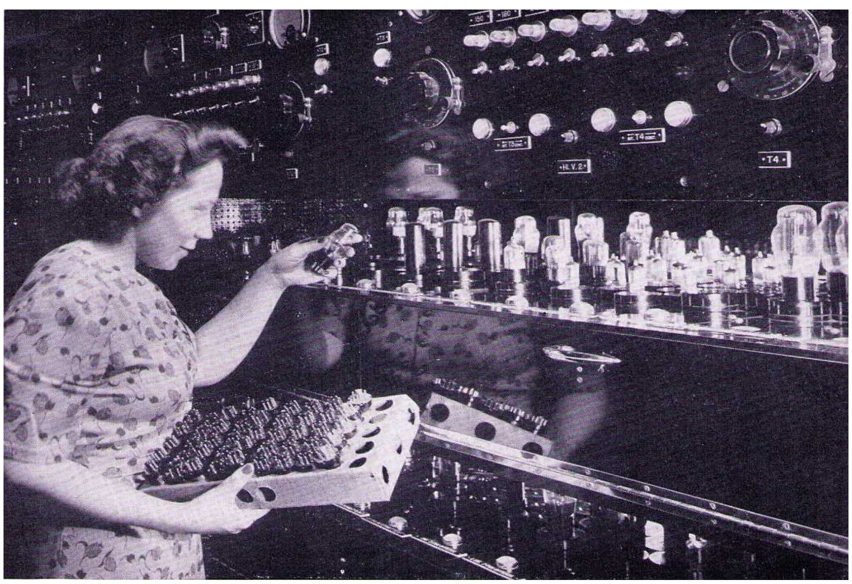
This article, courtesy of Bill Bright, gives an unusually straightforward discussion of the failure mechanisms of tubes and ways to avoid them. It covers, for example, the start-up stresses on tube heaters in series-string operation (years before the big swing to controlled warmup time), and the audio hum arising in heaters. It gives a sales pitch for the RCA "Special Red" line of 10,000-hour tubes - less the 5690 rectifier, on which the developers were still struggling to reach the required life. - Ed

A SINGLE TUBE FAILURE in industrial electronic equipment may cost the equipment user hundreds of times the price of the tube. Tube failures often are caused by improper equipment design practices, particularly in cases where receiving-type tubes are used in industrial applications. Considerable progress has been made in programs aimed at increasing tube reliability in industrial circuits. Of particular importance are the ways in which the circuit designer may prolong the life of the tubes.

More industrial-type tubes are now available to equipment designers — tubes designed for specific industrial applications. Often, however, new circuit applications require particular tube characteristics which are as yet available only in receiving-type tubes. When these tues are used, special care must be taken to insure reliability in operation. Receiving-type tubes are designed for use in home instruments, where it is unlikely that they will be subjected to extremes of temperature, to excessive shock and



Preburning is an effective way of weeding out unreliable electron tubes before installation in equipment. However, such aging is a costly and time-consuming addition to mass production techniques.

vibration, or to various other severe environmental or operating conditions encountered in industrial equipment.

In cases where it is necessary to use receiving-type tubes in industrial circuits, certain equipment design practices may be employed to increase reliability. Many such practices will be discussed in this article. All of them are important to the designer.

RANGE OF TUBE CHARACTERISTICS

Practical considerations, such as production speeds, testing problems and material costs, often fix the range of tube electronic characteristics at ±20 to 40 percent of design-center values. Even on special industrial types, where tighter controls and premium materials are economically feasible, characteristics may have tolerances of ±10 to 20 percent. These tolerances are caused largely by variations in dimensions of internal parts and in chemical properties of inner tube surfaces. The tolerances also reflect some unavoidable shifting of characteristics from one manufacturing lot to the next.

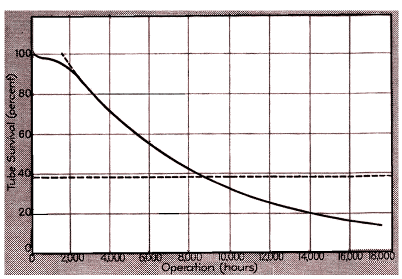


Fig. 1. Survival curve of a filamentary triode-type tube. Average life is the point at which 37 percent of the tubes are still in operation.

In a particular high-impedance triode, for example, typical manufacturing tolerances are in the order of ±1 percent on coated cathode diameter; ±1½ percent on grid diameter; and ±2 percent on plate diameter. A cumulative variation in characteristics of ±5 to 10 percent due solely to such tolerances on parts can exist in an appreciable number of these tubes.

Tube characteristics are also affected by such factors as degree of activation of the cathode over its length; contact potential between grid and cathode; and tendency toward secondary emission. And since complete stabilization of all tubes by pre-burning is not practical, wide variations in initial characteristics are normal. For example, because traces of metallic or gaseous contaminants on electrode surfaces affect contact potential, it is impractical to control the grid contact potential to limits closer than ±0.3 volts.

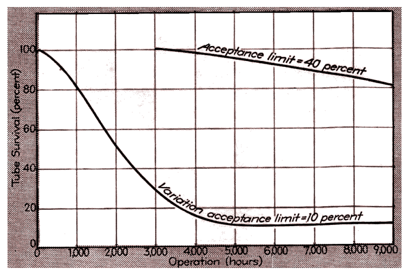


Fig. 2. Typical survival curves for tubes in which variations of 10 and 40 percent in transconductance are allowable. Circuits should be designed for wider variations in tube characteristics.

Because characteristics do vary from tube to tube, and also because many tube characteristics change during life, it is well to design circuits for operation over a wide range in tube characteristics. Life tests on a typical tube show that its average life is increased 2½ times if the acceptable change in transconductance is doubled. And the average life is increased 5 times if the acceptable change in plate current is doubled.

From the standpoint of reliability, however, the equipment designer is more interested in percent survival of tubes than in average tube life. For example, he would rather know that all tubes will last 1,000 hr than know that average life is 5,000 hr with a few tubes failing before 1,000 hr and a few lasting longer than 10,000 hours. Unfortunately, the latter case is closer to actual experience. In general, the survival of tubes in operation is typified by Fig. 1, in which the curve follows an exponential law after 2,500 hours.

The effect of wider tolerances for tube characteristics on survival is illustrated in Fig. 2. Percent survival vs hours of operation is plotted for maximum allowable transconductance changes of 10 and 40 percent, respectively. If the desired reliability criterion is survival of 80 percent of the tubes, it can be seen that a transconductance limit of 10 percent change yields 1,000 hr life, while a limit of 40 percent change yields 9,000 hr life. Often, tube life may be further extended by providing means of adjusting circuit conditions, at least initially.

PRE-BURNING AND TUBE SELECTION

Tube failures may occur in significant number during the early hours of life. Many of these failures are caused by opened welds or shorted elements. Other early failures are caused by sudden

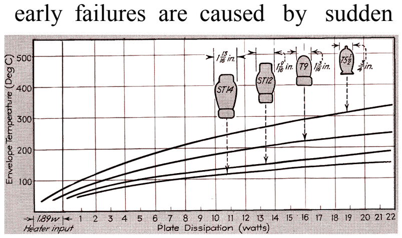


Fig. 3. Envelope temperatures as a function of input power for various sizes of glass tubes. Excessive temperature can shorten the life of any tube and is a more critical problem in the smaller-envelope sizes.

shifts in tube characteristics to values outside acceptable limits. To improve tube reliability, many industrial users pre-burn tubes for 50 to 100 hr under conditions simulating intended applications to stabilize characteristics further and also to eliminate early mechanical failures. Tubes designed specifically for industrial service often receive a similar 50 hr stabilizing burn-in as part of the standard manufacturing processing. Pre-burning of all mass-produced tubes is, of course, impractical.

To get a desired range of tube characteristics an equipment designer sometimes is tempted to select, from available stocks, tubes having tolerances closer than tube manufacturers provide. If the quantity of tubes involved is sizable, however, this practice can be costly. Furthermore, there is no assurance that the yield of tubes with the desired range of characteristics will be maintained in future production. Such an arrangement also poses tube replacement problems for the equipment user.

In industrial service, successful operation of a circuit often depends on some tube characteristic for which there is no published information. In such cases, the tube manufacturer can advise the equipment designer as to how closely a given tube type does maintain the desired characteristic. The tube manufacturer may suggest another type in which the critical characteristic is controlled more closely.

MAXIMUM TUBE RATINGS

Maximum tube ratings set by tube manufacturers are the limits within which tubes must be operated for satisfactory performance. Ratings for receiving-type tubes, in general, are not as conservative as those for industrial types. Therefore, when receiving-type tubes are used in industrial circuits where longer life is desired, maximum ratings must be re-evaluated.

When several maximum ratings are given it is not wise to assume that one rating (for example, plate voltage) may be exceeded, provided that a corresponding reduction is made in the other ratings. The first maximum rating reached should set the limits for all other conditions.

The operating frequency is another factor to be considered. When tubes are operated at high frequencies, the internal tube losses increase, reducing efficiency and, therefore, permissible maximum input. Dielectric losses in the glass stem between lead wires may increase sufficiently at high frequencies to raise the glass temperature and hasten electrolysis failure. Rectifiers operate at high temperatures and high inverse voltages and, therefore, are particularly susceptible to electrolysis. At high frequencies, dielectric losses in the glass envelope near points bombarded by stray electrons may increase sufficiently to overheat the glass, causing cracks or evolution of gas from the glass envelope. In all cases, therefore, the permissible tube dissipations for maximum reliability are lower for operation above some critical frequency.

ENVELOPE TEMPERATURE

Tube life may often be extended by maintaining envelope temperatures at low values. This is especially important in power-output types because of their higher plate and heater dissipations. The temperature rise of the envelope may be limited by: (1) reduction of total tube dissipation; (2) provision for improved ventilation; and, (3) maintenance of low ambient temperatures. In general, the envelope temperature of small receiving-type power tubes should be kept below 175°C for increased reliability.

The tube envelope, as well as other glass and metal surfaces within the tube, holds by adsorption and absorption small amounts of gases. If released during tube operation, these gases cause poor performance. In receiving-tube processing, the degassing process includes heating of all parts to drive off gases, mechanical evacuation of the tube by high-vacuum pumps, and chemical clean-up of gases within the tube by gettering materials. All but minute quantities of adsorbed gas are removed from the glass envelope. The complete removal of adsorbed gas from the glass envelope would require hours of baking at temperatures of 250 to 300 °C, which is impractical for high-volume receiving types. If, during subsequent tube operation, envelope temperatures equal or exceed those used on exhaust, some of the remaining adsorbed gases will be liberated. A limited amount of these gases can be absorbed by the gettering material, but excessive gas evolution results in minute traces of free gas in the tube.

The presence of free gas in a tube an be undesirable for a number of reasons. The gas molecules may become ionized due to collisions with electrons during tube conduction. These ionized molecules migrate to the negative electrodes in the tube. Those traveling to the control grid are equivalent to an electron flow from the grid and produce across any grid circuit resistance a voltage drop which ends to increase the flow of cathode current. In addition, if ions arriving at negative grids are sufficiently energized, they knock out electrons and use reverse or secondary emission from the grids.

Gas ions arriving at the cathode may dislodge cathode coating material by bombardment. Furthermore, because the hot cathode has a great affinity for gas, ions arriving at the cathode combine with the free barium, so that emission is gradually reduced. Thus, envelope temperature is more critical for tubes having smaller cathode areas.

The envelope temperature is a function of the heat generated within the tube, the envelope size, and the ambient temperature. The relationship of envelope temperature to total power dissipation for tubes of various sizes operating in air of normal room temperature (approximately 30°C) is shown in Fig. 3. The temperature of the plate and screen electrodes of tubes results primarily from the conversion into heat of the energy of electrons arriving at these electrodes. Typical operating temperatures for the plate and screen electrodes of power pentodes are of the order of 400 to 450°C. Plate temperatures for triode types range from 300 to 400°C, depending upon the power input. Any increase above these temperatures results in envelope temperatures which are increasingly troublesome. In addition, the probability of release of residual gases from the parts is increased.

The ambient temperature can be controlled by good ventilation, using blowers if necessary. Reductions in envelope temperature have been obtained with miniature and subminiature tubes by the use of close-fitting metal jackets thermally connected to the chassis so that the chassis serves as a heat-radiating surface or by shields designed to cool the envelope with convection currents. When a solid bond to the chassis is not made, the use of conventional metal shields around tubes can raise envelope temperature as much as 50°C. To promote heat radiation, plated shields should be avoided and surfaces surrounding the tube unpolished.

CATHODE TEMPERATURE

For long life, oxide-coated cathodes must be operated at recommended temperatures. For most tube types, ±5 per-cent of rated value is the maximum allowable heater-voltage variation for long life. Because industrial electronic equipment often must operate with varying line voltages, regulation of heater voltage should be considered.

At cathode temperatures above recommended values, evaporation of free barium from the cathode surface is accelerated, and cathode emission decreases with time to values insufficient for certain applications. This effect is most serious in the case of power-output and rectifier types, where normal cathode temperature is relatively high to provide the abundant emission required for satisfactory performance.

Elevated cathode temperatures cause the deposition of vaporized emitter materials on tube electrodes such as grids or plates, or on surfaces of glass or mica insulators. Such deposits increase the tendency of electrodes to become emitters during operation, and may cause undesirable reverse currents to flow. If such currents flow in a grid circuit containing high resistance, the voltage drop produced often upsets normal functioning of the tube. Higher cathode temperatures in turn cause higher operating temperatures of other electrodes and increase the possibility of reverse emission. Deposits of emitter material on insulating surfaces may give rise to noise or faulty insulation between electrodes.

On the other hand, when the cathode is operated below recommended temperature, emission decreases and may go below the safe limit required to maintain desired tube characteristics over a long period of operation, especially in applications requiring high peak current or power. A phenomenon known as sparking may result from the emission becoming confined to localized spots of high current density in the cathode.

A more common effect of low-temperature operation is poisoning of the cathode because of gas absorption. The lower the cathode temperature, the more readily it absorbs gas. Very small amounts of oxygen or carbon monoxide poison a cathode (i. e., drastically reduce its emission).

If voltages are applied to other electrodes while the cathode is below operating temperature, ion bombardment of the cathode may cause permanent damage to the cathode coating. After the cathode has reached operating temperature, the electron cloud surrounding it neutralizes ions arriving there and prevents damage to the coating. Thus, where equipment is subject to many cold starts, the life may be extended by applying electrode voltages only after a cathode warm-up.

GRID RESISTANCE

In the present stage of the tube-manufacturing art, grid currents of the magnitude of one microampere may be present in receiving-type tubes. The designer, however, can frequently compensate for this grid current by using the smallest practicable value of grid resistance. This precaution is necessary because excessive grid resistance may produce "run-away" tubes. Whatever negative grid current exists flows through the grid resistor, causing a shift in bias that is proportional to the value of resistance. For instance, a negative grid current of one microampere through a grid resistance of one megohm decreases the negative bias by one volt. The bias shift tends to increase plate current.

A larger plate current increases ionization collisions and thus ion current to the grid, which, therefore, swings even less negative. If grid resistance is too large, this effect may be cumulative, so that plate current reaches destructive values.
Negative grid currents may result from ionization of residual gases, grid emission, or leakage across insulation inside the tube or externally across the tube base. An additional reason for reducing grid resistance is that high grid resistance increases the susceptibility of the circuit to the pick-up of undesired voltages. Transformer coupling between stages of amplifiers is often advantageous for obtaining low d-c grid resistance. Usually, the grid resistance should be kept under 200,000 ohms for power-output types and under 2 megohms for all other types. Cathode-resistor bias, by virtue of its effective degeneration, may be used to minimize the harmful effects of larger grid resistances.

OPERATION OF HEATERS

When full heater voltage is applied to a cold heater, the heater assembly is subjected to thermal shocks and strains caused by expansion and unequal heating of the heater wire. Expansion causes physical abrasion against the cathode, especially near the cathode ends. During warm-up, strain is also placed on the heater welds at the stem leads. A high rate of on-off switching may cause heater failure due to fatigue.

In many installations it is possible to maintain continuous operation, and thus to reduce the frequency of switching. Or, by applying or removing heater voltage gradually when the equipment is turned on or off, heater failures can be virtually eliminated.

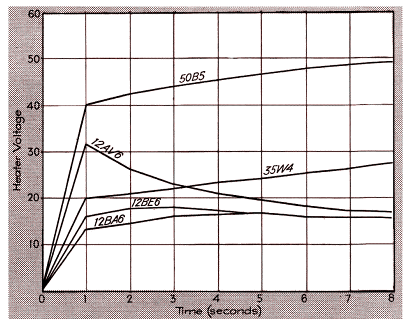


Fig. 4. Initial heater-voltage surges in series-string operation of five different receiving tubes. Type numbers of tubes are indicated on the curves.

In general, low-voltage (6.3 V) and high-current (300 milliamp or more) heaters, because of their heavier wire, are better than high-voltage or low-current heaters for reliability.

Under certain conditions, series-string operation may represent very severe service. For purposes of illustration, a conventional receiver uses types 12BA6, 12BE6, 12AV6, 50B5, and 35W4 with all heaters connected in series. If the heaters are all at room temperature, then at the instant voltage is applied to the heaters a current of the order of 6.5 times the "hot" current flows through the heater string. The 12-V heaters have lower thermal inertia, and so they show a more rapid increase in heater resistance and temperature than do the 50B5 and 35W4. As a result, initially most of the line voltage appears across the three 12-V heaters.

The curves of Fig. 4 show that within the first second after voltage is applied to the heater string, the voltage across the 12AV6 rises to 31.5 volts, while the voltage on the 35W4 and the 50B5 remains well below rated values for five seconds or more. The effect on the 12AV6 heater voltage of replacing part of the series string with a resistor is shown in Fig. 5. Replacing the 12BA6 with an 89-ohm resistor reduces the peak heater voltage on the 12AV6 by 20 percent. Replacing the 35W4 with a 247-ohm resistor reduces the peak voltage by approximately 30 percent to 21 volts. In addition, the rate of rise of heater voltage is decreased as the series resistance is increased, further reducing thermal shock to the heater.

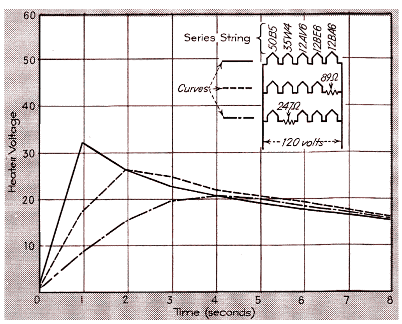


Fig. 5. Curves illustrating the effect of inserting resistance in series with a heater string. Legend at top right identifies the curves.

The effects of series-string operation are aggravated by the fact that the temperature is not uniform along the length of the heater, but may be concentrated in small sectors such as the uncoated sections of wire near the stem lead welds. On tube types having a cathode of small mass and low thermal inertia, the heater temperature may rise to a value that will cause sintering of the heater insulation.

If series-string operation is unavoidable for particular applications, the following will improve reliability.

1. Use tubes with less than 300 milliamp heater current.

2. The total heater voltage of slow-heating types should be less than half the total string voltage. Limit the surge voltage across any heater to less than twice the rated value.

3. A resistor should be used in series with the heater string to make up at least 15 percent of the load.

4. Series-parallel combinations should be avoided. A resistance in parallel with part of the heater string increases voltage surges. For instance, if a resistor is used across a 150-milliamp heater to include it in a 300-milliamp string, the 150-milliamp heater passes a greater current initially than it would in a 150-milliamp string. If possible, high-current heaters should be used in one string and low-current heaters in another.

STANDBY AND CUTOFF OPERATION

During vacuum-tube operation, a layer known as the interface gradually forms between the cathode base metal and the cathode coating. If, however, the tube operates for long periods of time while biased beyond cutoff, this interface layer may take on characteristics equivalent to those of a cathode resistor of a few hundred ohms shunted by a capacitance of 0.01 microfarad, resulting in faulty circuit performance. In some cases, cutoff life is as little as 5 percent of average conduction life. However, if the minimum cathode current can be maintained greater than 0.5-1.0 milliamp, harmful effects of the interface layer can usually be avoided satisfactorily.

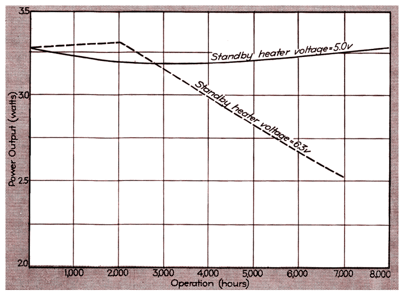


Fig. 6. Effect on life of reduced heater voltage during standby operation of a typical receiving tube. If such usage is needed, tube life can be extended by applying reduced heater voltage during standby.

Some cathodes exhibit this interface characteristic and others do not, depending to a large degree upon the composition of the cathode base metal. Because receiving-type tubes are designed for the requirements of radio service, where cutoff operation is not a problem, these types may not have a satisfactory "cutoff-life" characteristic. Several industrial tube types are made with relatively "inactive" cathodes to improve performance in applications where cutoff life is important.

Standby or heater-only operation produces effects similar to those of cutoff operation, and should be avoided where possible or at least restricted to short periods of time. If standby operation is required, tube life may be extended, as demonstrated in Fig. 6, by operating the heater at reduced voltage during standby.

SHOCK AND VIBRATION

Conditions of shock and vibration may cause a tube to fail by shifting its characteristics, by causing a short between elements, or by causing an open circuit in one of the elements.

Receiving tubes are generally not designed or tested to withstand unusual shock or vibration. Tubes designed for industrial service, however, incorporate features that make them less suspectible to shock and vibration failure. There is a limit, nevertheless, to how far tube design can accommodate shock and vibration and still provide desired electrical characteristics. Beyond this point shock and vibration must be reduced or eliminated by suitable shock mounting of equipment and tube sockets. Much can be done even with standard tubes by proper shock mounting. All electrical connections to a shock-mounted socket should be flexible or the purpose of the shock mounting may be defeated. If vibrations are air-borne, damping of the tube with lead may be required.

NOISE AND HUM OUTPUT

Although most industrial applications do not require critical limitations on noise or hum output, several methods may be used to reduce tube noise or hum where necessary. Electromagnetic and electrostatic fields set up within the tube envelope by the heater may produce a hum voltage in the tube output circuit. Such hum can be nullified by a hum-balancing potentiometer connected across the heaters with the center-tap connected to ground. Often sufficient balance is obtained merely by connecting the heater transformer center-tap to ground.

Hum output may also be caused by leakage through the heater insulation material. As shown in Fig. 7, the resistance of the insulation varies with d-c bias, the lowest value of resistance occurring within a volt or two of zero bias.

When a heater-cathode type tube is operated with cathode-resistor bias, it is possible that leakage through the insulation between the a-c operated heater and the cathode will be sufficient to develop voltage across the cathode resistor. The undesirable effects of such a voltage can be avoided if the cathode resistor is bypassed with a capacitor of 25 microfarads or more. If bypassing is not possible, a d-c bias of 5-60 V positive or negative applied between heater and cathode shifts the operating point to the relatively flat portion of the curve, as shown in Fig. 7, and the hum current is reduced considerably.

The undesirable characteristic known as microphonism must also be considered in high-gain amplifier design. A tube is microphonic when, with no input signal, it gives rise to an output voltage while it is being lightly tapped with a felt mallet. Microphonism is a resonant effect. The microphonic output is the result of resonant vibration of some internal tube structure. If the microphonic tube is acoustically coupled to the audio output of the amplifier of which it is part, sustained oscillation may result. Tube manufacturers have gone to extensive measures to control microphonic characteristics of critical tube types. But in spite of all precautions, some microphonic tubes undoubtedly will appear good during testing and pass inspection.

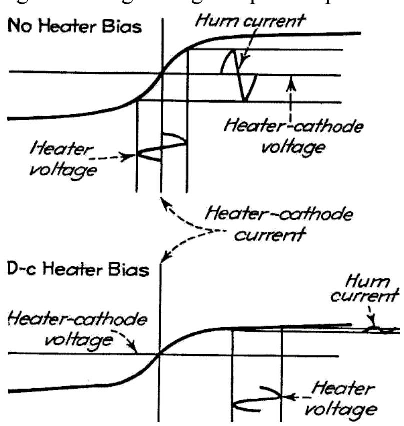


Fig. 7. Resistance characteristics of heater insulation material, showing effect of d-c heater bias on hum. Leakage of current through the heater insulation can have undesirable effect on operation.

Shock-mounting the socket will isolate the tube from the chassis as a source of vibration or shock. If the acoustic feedback is through the air, other components may be placed in the air path between the acoustic output and the tube, and the sound reproducer may be moved farther away. Where space is at a premium, the tube vibration may be damped by such means as weighting the critical tube with a cylinder of lead. Noises known as thumps, clicks or pops may be detected by testing, and tubes exhibiting these noises can be removed from critical stages and used in the less critical later stages.

SOCKET DESIGN

Industrial electronic equipment is often expected to operate at elevated temperatures, in corrosive, humid, or dusty atmospheres, and under conditions of vibration. Good tube-socket reducing the temperature of leads can improve circuit performance and reliability in such cases.

Tube sockets should be made of the best dielectric materials. The metal parts should be plated with corrosion-resistant material such as nickel. The socket contacts should grip the tube pins firmly without putting a physical strain on the rest of the tube structure, such as the glass stem of miniatures. In some cases, the use of shields that lock to the base is required to keep the tubes secure in the sockets.

The use of heavy wiring for connections to the tube socket terminals promotes longer life in some cases by reducing the temperature of leads within the tubes. If leads run too hot, rectifiers will have shorter lift due to electrolysis of the glass between the leads. In certain tubes such as power-output tubes, where grid temperatures tend to run high, heavier electrical connections are used to reduce the grid temperature and prevent grid emission. In such cases, good thermal of the socket terminals and of the wiring to the gird may help.

TUBE MAINTENANCE

The designer of industrial electronic equipment should consider the problem of maintenance, including availability of replacement tubes, frequency of tube maintenance routines, and the manner of testing tubes. Ease of maintenance is often a key to reliable operation.

A common practice in industry is the replacement of tubes on a periodic schedule regardless of their condition. It is doubtful that this method insures any greater reliability, because tube failures in operation follow a logarithmic pattern (Fig. 1), with some tubes failing in a few hours and others lasting several thousands of hours. The automatic replacement schedule neither eliminates early failures nor obtains the benefit of the better tubes having long useful life.

In general, tube failures may be classified as sudden or gradual. The sudden failures are due to such causes as shorts between elements and open elements, and usually occur early in life. They are unpredictable, but may often be reduced by a pre-burning operation before actual use in equipment.

Most tube failures, however, are due to the gradual decrease in emission or transconductance, and can be detected before performance is below minimum requirements by periodic tube checks. Preferably these checks should consist of measurement of tube performance in actual operating equipment. To facilitate such tests, the designer should provide easy access to tube sockets or special testing connections brought out to convenient terminals. The tests should indicate the margin of safety remaining in critical operating characteristics.

A refinement of this technique is the "Marginal Checking" system in use on at least one large electronic computer. This system consists of changing operating conditions (such as supply voltages, signal levels, etc.) in such a manner that the computer will misperform if tubes of marinal performance are present. Additional means are provided for making such checks on small sections of the computer to localize a failure rapidly.

INDUSTRIAL TUBE DESIGNS

Circuit reliability can best be obtained by using the available industrial-type tubes whenever possible. Examples of such tubes are the RCA-5691, 5692, and 5693. As illustrated in Fig. 8, many special features have been incorporated in the industrial types to insure reliability in specific industrial applications.

Long life is also built into these special tubes as the result of: (1) designing the cathode to operate at relatively low temperatures; (2) maintaining exacting control during processing to prevent deposit of cathode materials on other electrodes; (3) using pure-tungsten heaters provided with sleeves to give long heater life with frequent "on-off" switching; (4) inspecting each assembly for adherence to rigorous specifications; (5) rating the tubes conservatively; (6) using inactive cathode base metal for good cutoff life.

All industrial tubes are given a stabilizing 48-hr aging before testing. Tests are made for more characteristics and to tighter limits than on receiving types. For example, the published characteristics state that the maximum value of reverse grid current is 0.2 microamp for type 5691 and 5692 and 0.1 microampere for type 5693.

These features combine to make a tube having a minimum life of 10,000 hr, exceptionally uniform and stable characteristics, and resistance to shock and vibration.

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