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## IN THIS ISSUE



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# A SIMPLE SOLID-STATE COLOUR ORGAN

## Introduction

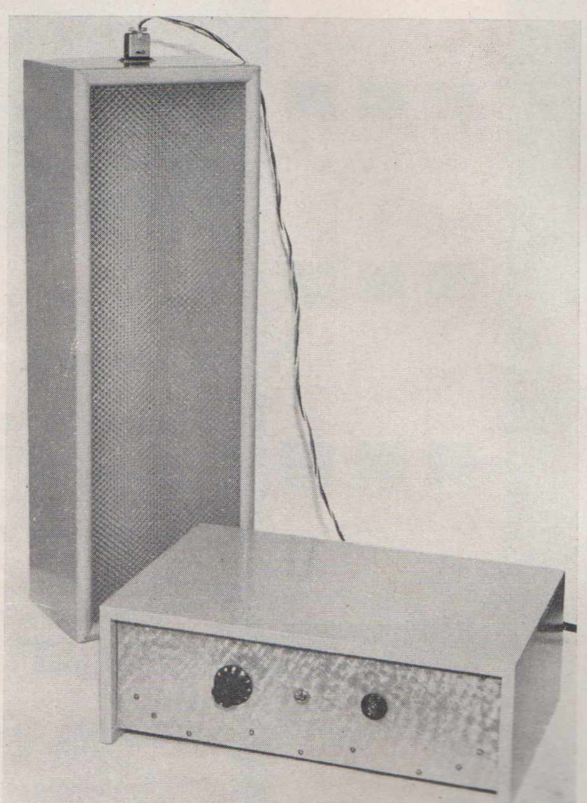
The circuit to be described here is of a type variously referred to as a colour organ, or by the more impressive name of a photorythmicon. The object of the device is to separate the output of an audio amplifier into three bands of frequencies, and then to use the three bands of frequencies to light coloured lamps. The colours of the lamps correspond to the bands of frequencies which energise them, and the strength of the illumination to the loudness.

The three lamps, or three groups of lamps, are generally set up in a display in which some mixing of the outputs is obtained, and in which an attempt is made to create a visual sensation corresponding to the music being played. The methods of achieving all this, both the separation and amplification of the bands of frequencies, and the subsequent employment of them in a display, are several, and depend on how ambitious a display is required, and how much the user can afford to spend.

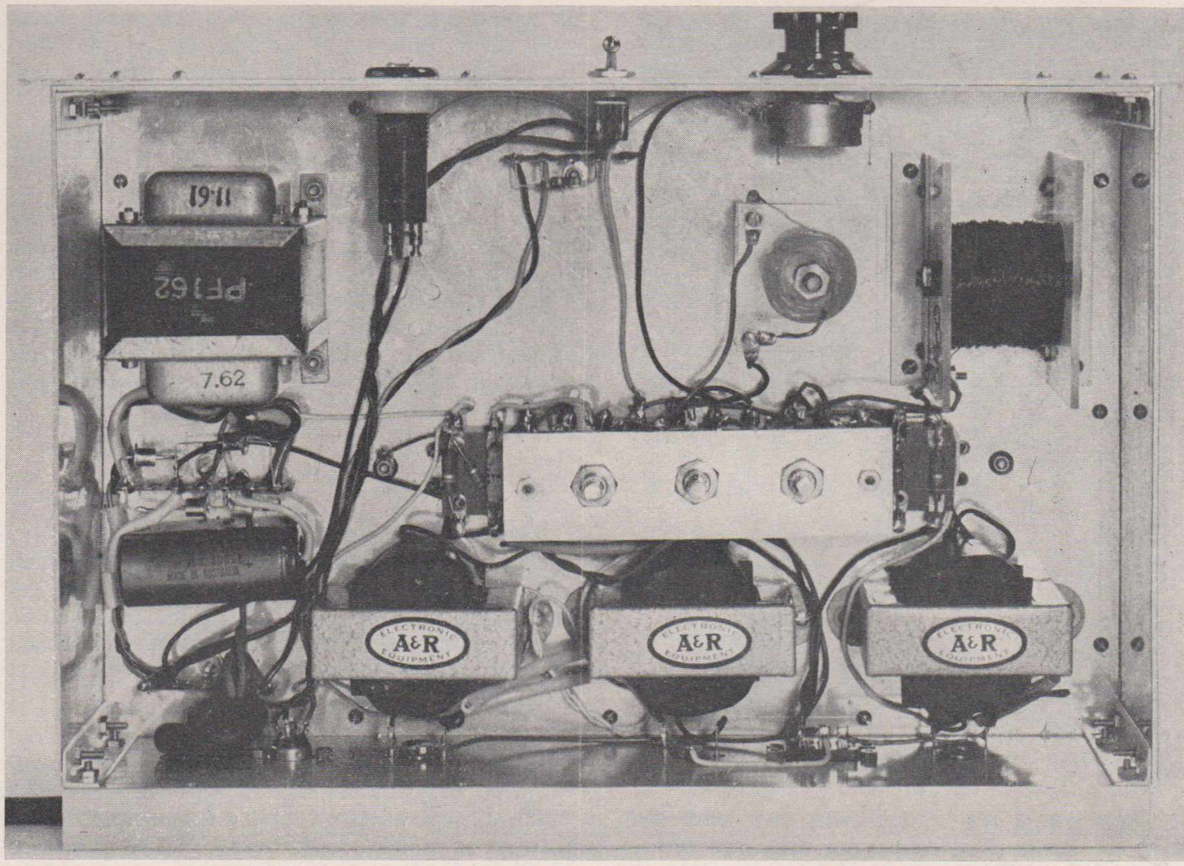
This is not the type of project to which these pages are usually devoted, but as we had experimented with such a unit, it was felt that some readers may be interested in the idea from an amusement point of view. Most readers will not be aware of the fact, but several demonstrations of amplifier circuits featured in these pages have been given over recent months, and our original interest in the colour organ arose from a desire for a point to lighten a somewhat technical discussion at these demonstrations. The amusement caused by this, and the interest expressed by many people to have further details of the unit, have led us to prepare this description.

## Philosophy

In the design of a unit of this kind, one generally finds that several decisions have to be taken cold; that is, without a complete set of data on



The two units forming the colour organ are the control amplifier and the light display unit.




**Photograph showing the internal arrangement of the control amplifier.**

the considerations involved. There is, for example, the choice of the three colours to be used. Here, psychologists could probably make great play with the effects of various colours upon people and the types of feelings that they arouse in the subject. It would naturally be possible to employ more than three colours if desired, but three was chosen as a reasonable compromise. The three colours chosen were red, amber and blue, corresponding to the bass, middle and alto bands of frequencies. The choice of colours was dictated partly by a consideration of the available colours of lamp dyes.*

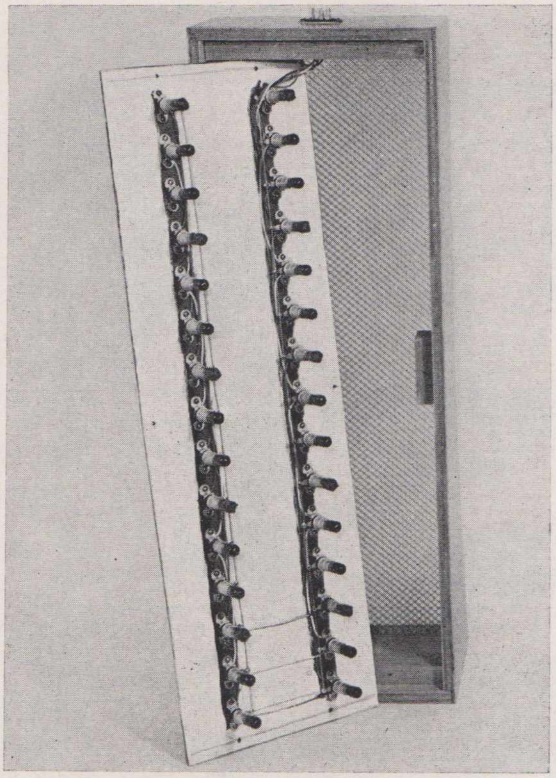
Another point on which data is always likely to be incomplete is the choice of the cutoff points which separate the musical spectrum into three bands. It will be obvious that, at least to some extent, this decision could be swayed by the nature of the music being played, so that with all the data in the world, the final choice is still likely to be a compromise or an educated guess.

* Whilst proper lamp dyes, which are available from the larger electrical warehouses, can be used, experiments could also be made using any coloured transparent medium, such as coloured "Cellophane" or other wrapping material. The lamp dyes are a special formulation with high transparency, and made to withstand the heat from normal domestic-sized lamps. The heat generated in the lamps in this unit is quite low under normal operating conditions.

Another factor concerns the variation of light intensity with sound volume. The difficulty here is that the dynamic range of musical programmes is greater than the dynamic range of a lamp. In some devices of this nature, the attempt to vary the light intensity has been abandoned, so that we have a device that lights a lamp or lamps in a group to a standard brilliance whenever a frequency within the corresponding band is present in the programme material. Most people will feel that this simplification will inevitably loose an essential part of the visual sensation that we are trying to create.

The answer to the problem of dynamic range would appear to be the use of some form of compression within the colour organ. This has not been done in the circuit to be described here, not because it presents any difficulties, but simply because we have not had the time to do so.

The response of the human eye to stimulus by different colours is not the same, so that, while any such unit must incorporate means to adjust the illumination of each individual group of lamps, this adjustment cannot be carried out for equal current through the lamps under the same amount of drive, or in any similar fashion. The final adjustment of the intensities of the groups of lamps could presumably be based on the spectral



**This view shows the light display unit, with the board on which the lamps are mounted withdrawn from the case.**

characteristic of the eye, but in actual fact is just as easily done subjectively, using programme material which is known to possess a wide frequency coverage.

In theory, of course, if the three primary colours were used for the lights, and suitable mixing of the outputs could be arranged, the final display could be made to include all visible colours. Whilst the unit we constructed has some mixing, no attempt has been made to follow this line of thought to its conclusion, largely because it was felt that music, with its constantly changing nature, would not in fact allow us to realise this potential goal. Such simple experiments as have been made appear to support this view.

Readers will be aware of the fact that lamps have thermal inertia, which varies with the type of lamp. In the case of flash-lamp bulbs, this inertia is very small, and as far as the eye can tell, the illumination and extinction of such a lamp is almost instantaneous. If, on the other hand, we examine a car headlight bulb, we find that the eye can detect a delay in the lamp attaining full brightness, and also in its quenching. If we use quick-acting lamps in our display unit, then the appearance of a particular colour, and the degree of illumination, will coincide, for all practical purposes, with the programme material to which we are listening. On the other hand, slow acting lamps will have an integrating effect on the display, so that the display, whilst it may be of interest, will not reflect the programme faithfully, and will not contain those transients which enliven music and add to its character. Fast-acting lamps are used in this display.

All this, and there are many other considerations that the alert reader will find to think about, appears to be a lot of philosophy to use over what is in effect a toy. Like all such mental exercise, however, it is beneficial, in that it helps to give a better appreciation of the operation of the device in addition to the more fundamental considerations involved.

## The Amplifier

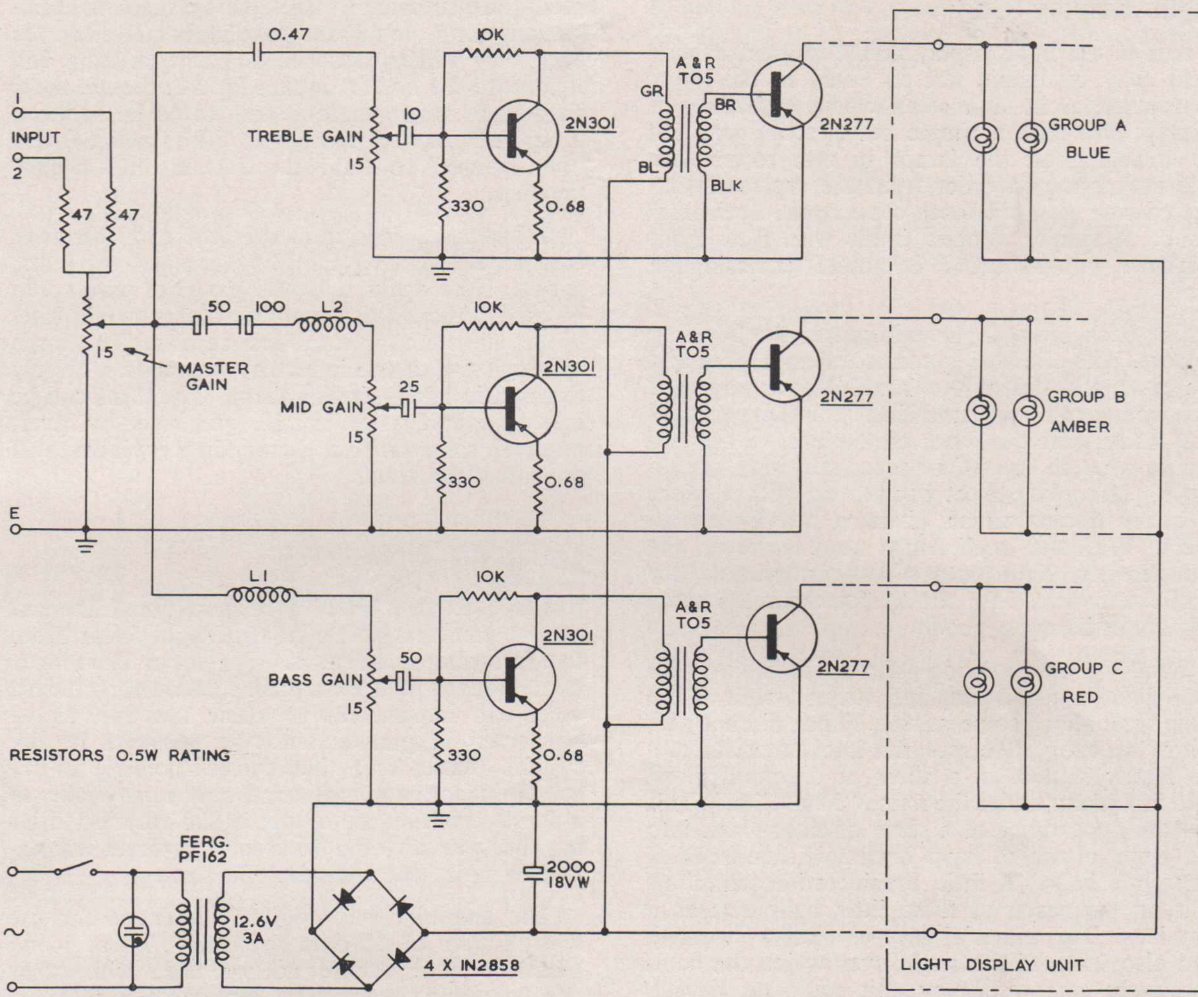
The colour organ described here is based on a circuit published overseas over a year ago. Some of the changes made have been to adapt the original circuit to use locally-available parts, some, in our opinion, to improve operation. The colour organ is divided into two parts, the amplifier and the light display unit.

The amplifier receives the programme material, divides it into three bands of frequencies by means of three very simple filters, and then uses each band of frequencies to control the current flowing through a group of ten lamps. This means that the light display unit contains three groups of ten lamps each, a total of thirty lamps.

The accompanying circuit of the amplifier shows an input adapted for stereo reproduction, in which the two input leads are connected in parallel with the speaker connections for each channel. A simple resistive mixer provides us with a mono channel, which then becomes the signal which we are going to process into the coloured display. The derivation of a mono channel from the two stereo channels, instead of using one of the stereo channels only, was felt to be essential, particularly having regard to some of the "engineered" records that are with us today, with exaggerated separation.

The three very simple filters shown in the amplifier circuit are, reading from the top of the circuit, high-pass, band-pass and low-pass. The accompanying diagram of the overall response of the amplifier through the three channels shows that the filters are very flat, which is what is wanted. It also appears to show that all three filters have a band-pass nature, but this is due to the fact that the overall response of the amplifier in the bass and alto regions is also affected by the response of the transformers used in the amplifier.

Each channel contains an AWV 2N301 transistor, which is transformer-coupled to a 2N277 or any transistor of the same family. The lamps used in the light display unit are 6.3-volt 150




**Circuit diagram of the control amplifier unit.**

(Since this unit was made, 1N2858 has been superseded by 2N3193)

milliamp types, so that 10 of these require 1.5 amps to energise them, almost 9.5 watts. This explains the use of a large power transistor in the final stage of each channel.

Because there are no considerations of quality involved, a very simple power supply is used, consisting only of transformer, four diodes in a bridge circuit, and a large filter capacitor. The transformer used in the model is a Ferguson PF162, which is a heater transformer with two 6.3-volt 3.0 amp. windings. The windings are connected in series to produce a collector supply of about 18 volts under no-drive conditions. Whilst the transformer is not rated for 4.5 amperes, which is the total full load lamp current, to which would have to be added current through the six transistors, the fact is that under normal conditions, this state of affairs will be very rare, and the transformer and diodes are well able to cope with the situation.

The transistors in the circuit all operate in something approaching a class C condition, so that the idling current is quite small. Precautions should be taken during testing under steady tone conditions to see that extended over-running of components is avoided.

The construction of the amplifier is an easy task, layout being completely unimportant, and any shape or size could be used. The three 2N301 transistors develop very little heat under normal conditions, and the use of the chassis as the heat sink is adequate provision. The three 2N277s are provided in our model with a generous amount of heat sink, which also forms the back panel of the amplifier. Whilst the size of the heat sinks we used was to some extent dictated by the fact that we envisaged extended testing under steady tone conditions, it would be wise to retain as large an area as possible, as no other protection is provided for the output transistors.

## Light Display Unit

It is in the light display unit that great experiment may be made, not so much in the lights themselves, as in their arrangement and mode of display. We took a simple but effective way out by arranging all the lamps in two rows, with colours varying in order from the top, and with like colours alongside each other in the horizontal plane. A simple wooden frame with glass front was used, with a sheet of "Masonite" enclosing the back.

The back of the light unit carries the 30 lamp holders, with the wiring connected to a plug and socket at the top of the box. A four-way lead then connects to the amplifier. Some experiment was made with the front of the box to try and decide what to use. One successful idea was to use a plain glass sheet backed up with a piece of heavy tracing paper, giving a heavily frosted effect. With the small lamps used, however, the reduction in light output was undesirable for public demonstrations, though for use in the home this could be quite good.

What we were looking for was something with good light transmission, and which would at the same time afford some mixing. Time did not permit of an exhaustive research into materials, and we finally settled on a sheet of obscured glass, sold in Sydney under the name "Rondelite." This has the appearance of a sheet of clear glass, into the front of which have been laid hundreds of tiny glass balls. A little consideration will show that, in use, each of these little balls acts as a tiny lens. This material gave us what we wanted, and also widened the angle over which the comparatively narrow display unit could be viewed. There are obviously hours of fun for young and old in further experiment with different materials.

## Filter Inductors

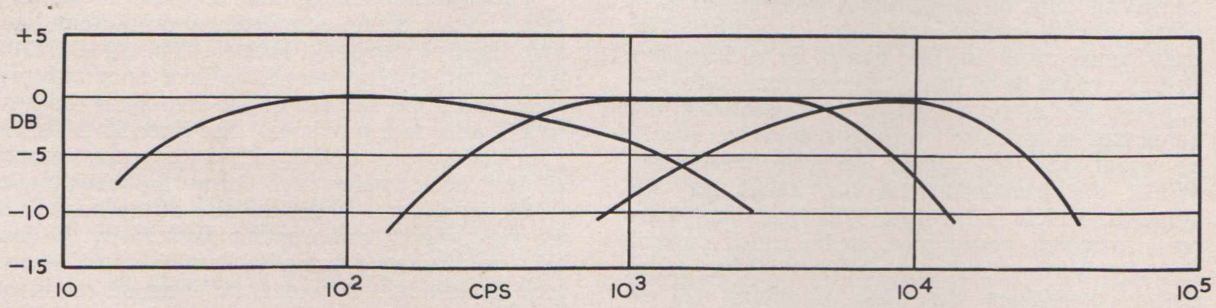
The two filter inductors, L1 and L2, are easily wound by hand. We used a 1″ diameter former, 1½″ long, for each inductor, with a ¼″ Whitworth clearance hole through the axis. Two cheeks were used with each coil to prevent the turns slipping off the end of the former; in our case, these were cut from ¼″ thick plastic sheet material, but anything would do, paxolin board, fibre, or even very stiff cardboard. The cheeks were 3¼″ square for L1 and 2″ square for L2, though these sizes were very generous and could be reduced if desired. In each case, a ¼″ Whitworth BRASS bolt is used to hold the former and cheeks together.

Inductor L1 in our model had 1300 turns of No. 48 SWG, and L2 225 turns of the same gauge. Here again, a lighter gauge of wire could be used, although the number of turns would have to be adjusted for the same results. The large physical size of the inductors was chosen largely to assist in hand-winding them. The turns can be laid on roughly side by side and layer by layer, although some random element in the winding will not affect the result.

## Using the Unit

There is very little to be said about the use of the unit that will not already be clear from the foregoing description. The input impedance of the unit is high enough in relation to standard voice-coil impedances to allow the unit to be connected in parallel with the speakers in any system. Make sure that correct polarity is observed; incorrect input connections may impose a short-circuit on the output of the amplifier driving the speakers, and with some types of transistorized unit, this will result in damage.

The amplifier was originally intended for use with a pair of 15-ohm speakers. There is no reason why it should not be used with other speakers, but it must be remembered that the lower the voice coil impedance, the lower the voltage across it for a given power output. The amplifier is fairly insensitive, responding on 15-ohm speakers to outputs of the order of 2 to 3 watts average in the speakers. Whilst this is satisfactory for public demonstrations, it could be too high for home use. However, the addition of a simple amplifier stage ahead of the filters presents no problem, but the filters should be fed still from a 15-ohm source to avoid a shift in characteristics of the overall responses.




**Response curves of the three amplifiers and input filters.**

For mono systems, the arrangement used in the original circuit could be useful. Here, the input mixer and input level adjustment were replaced with a 15-ohm T-pad, and about a watt was required to drive the unit. Direct connection across an existing voice coil would involve a change of load on the foregoing amplifier.

The possibilities for experimentation with a unit of this type are almost limitless. One interesting suggestion, for example, was that the lights, instead of being in a box, should be strung through a Xmas tree and appropriate music played. Before a flood of letters arrives, let us hasten to state that we have no intention of pursuing this unit very much further, and would prefer readers to try out their own suggestions rather than refer them to us.

# BOOK REVIEWS

**"Intermodulation and Harmonic Distortion Handbook," H. M. Tremaine, Howard W. Sams and Co. Inc., 160 pages, size $8\frac{1}{2}''$ x $5\frac{1}{2}''$.**

This book made an immediate impact on the reviewer because it appeared to gather into one place a great deal of information that is normally scattered through various sources in the literature. In keeping with the general tradition of the publisher, this title is not meant to be a highly scientific or mathematical treatment of the subject, but is written as an informative and very readable exposition of the basic theory. Dealing first of all with the theory of the generation of harmonic and intermodulation distortion, the discussion then turns upon some of the specialised equipment used in making measurements on these properties.

The discussion of equipment is illustrated with plenty of circuit diagrams, and concludes with a description of a laboratory analyser designed by the author. The rest of the book is then taken up with the techniques of distortion measurement, using the different known methods, and including enough sign-posts to enable those less well-versed in the art to avoid some of the pitfalls inherent in making such measurements. A useful handbook for anyone in the audio field, and, for its modest size, a veritable multum in parvo.

**"Transistor Circuits for Magnetic Recording," N. M. Haynes, Howard W. Sams and Co. Inc., 384 pages, size $8\frac{3}{4}''$ x $5\frac{3}{4}''$.**

This title deals with the practical application of transistor circuitry to magnetic recording equipment, and, of course, playback equipment also. The function and operation of the various circuits discussed are explained. Many of the circuits and techniques, whilst discussed here in the context of magnetic recording, have an application in other fields, including high fidelity amplification.

To discuss a book of this size and scope within a few lines is not possible. Suffice it to say that the treatment appears to be very thorough, and the book is bound to interest many whose direct interest does not necessarily reside in magnetic recording. Dealing first of all with the theory of transistors, the discussion passes to magnetic recording elements. Circuitry is dealt with under two main categories, sectional circuits, performing perhaps one or two functions, and system circuits, which deal with complete systems. The sections on system circuitry discuss several commercial circuits, and include chapters on FM recording and digital recording.

**"Transistor Amplifiers for Audio Frequencies," Thomas Roddam, Iliffe Books Limited. 252 pages, including 214 text illustrations.**

This is a practical book on the design of audio-frequency transistor amplifiers written by a man with wide practical experience of design. Mr. Roddam, who is a regular and popular contributor to "Wireless World," writes powerfully, and the reader is immediately aware that here is an author with a sure grasp of his subject and one on whom he can rely. Although this is an introductory work intended primarily for those new to the subject, even experienced designers will find there is much that they can learn from it. The book is essentially readable and the mathematics have been kept as simple as possible.

This title could be a useful addition to anyone's library, not only because it deals with general transistor physics and operation in a competent manner, but by reason of its specialising on the audio side.

# 2: Vacuum Phototubes

## Construction and Principles of Operation

In a vacuum phototube, one of the simplest of photodetectors, the essential elements are a photocathode, an anode, an envelope, and a suitable termination or base. The shape of the **photocathode** is determined by the particular optical requirements of the application and the general electron-optical requirement that electrons emitted from the cathode must be collected by the anode. The most common cathode shape is semicylindrical; one side is open to admit light and an anode rod is located approximately at the centre line of the cylinder. An ideal geometrical layout for omnidirectional response without interference from the anode is provided by evaporating cathode material on the inside of the envelope window to form a semitransparent cathode and locating the anode in the centre of the bulb. Cup-shaped cathodes have been used with ring-shaped anodes.

The **anode** of a vacuum phototube is usually made small to minimize obstruction of the light falling on the photocathode. As a result, the anode may not collect all the electrons emitted from the cathode. This situation arises because of the tangential component of the electron-emission velocity which causes some of the electrons to miss the anode and strike the glass window. When the energy of the electrons striking the glass wall is sufficient, secondary electrons are emitted from the glass and may be collected by the anode. If the secondary-emission ratio is substantially greater than unity, the glass window becomes charged to a positive potential, approaching that of the anode. If the applied voltage is too low to provide an effective secondary-emission ratio* greater than unity, the glass becomes charged negatively to approximately cathode potential.

Fig. 15 shows a perfectly cylindrical electric field in which the electron-emission energy is E electron-volts and the emission velocity is tangent to the surface of the cathode and in a plane normal to the axis of the tube. When the electron

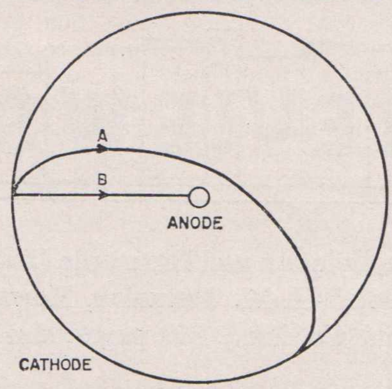



**Fig. 15—Paths of electrons in a tube having cylindrical geometry. Directions of emission velocities are (a) tangential and (b) radial.**

path is just tangent to the anode, or when the electron path impinges on the anode, a consideration of conservation of angular momentum and energy leads to the following relation:

$$\frac{b^2}{a^2} \leqq \frac{V + E}{E} \qquad (19)$$

Where b is the cathode radius, a is the anode where b is the cathode radius, a is the anode radius, and V is the potential difference between anode and cathode. For an electron energy of one volt and an applied potential of 100 volts, the anode radius must be greater than one-tenth the radius of the cathode in order to collect the

* Effective secondary-emission ratio is defined as the ratio of **collected** secondary-electron current (total secondary-emission current less return current) to primary current.

emitted electrons. In a typical construction, the radius of the cathode cylinder is approximately 8 millimeters and the anode radius is 0.5 millimeter. In this case, the number of electrons which strike the glass depends upon the wavelength of the exciting radiation.

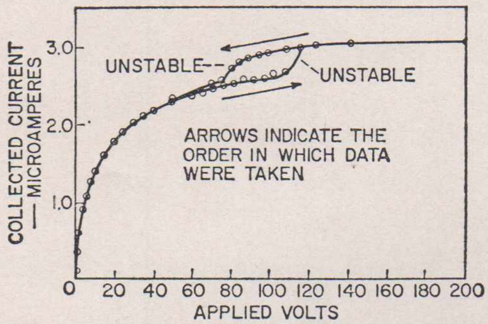



**Fig. 16—Erratic current-voltage characteristic in a vacuum phototube caused by bulb charges which result when the anode is too small to collect all emitted photoelectrons.**

Fig. 16 shows the sort of erratic behavior that occurs when the anode radius is too small (in this case the ratio of the cathode radius to the anode radius is about 30:1). Data shown are for a nonstandard 935 vacuum phototube having an anode-wire diameter of 0.020 inch (one half the normal dimension). The outside of the envelope was wrapped in a metal foil except for the window; the foil was at cathode potential. The phenomenon was also observed when the foil was at anode potential and when no foil was used.

On the lower branch of the "hysteresis" loop, as the voltage is increased, the glass becomes negatively charged. At the unstable point on the right, the secondary-emission ratio reaches unity; the result is an increase in the collected current. The top of the loop represents the condition in which the glass is positively charged. Although the case of Fig. 16 is an exaggerated one because of the small anode size, some instability of the output current is occasionally observed in conventional tubes. An anode voltage of about 250 volts eliminates the condition entirely.

The construction of the photo-tube stem and envelope follows the standard practices of the electron-tube industry. A typical construction is shown in Fig. 17. Choice of metals and glasses for specific sealing conditions is governed principally by their rates of thermal expansion. Table VII lists expansion coefficients for the more common glasses and metals used in the manufacture of phototubes.[1]

An essential process in the manufacture of most phototubes is the introduction of cesium. Although in some special phototubes cesium is introduced from a side tube, the most common method of introducing this activating material is by means of an activating pellet, as shown in Fig. 17. A mixture of cesium chromate and silicon is formed into a pill and held between the two sides of a metal container. During processing the activator container is heated to a dull-red color by the use of radio-frequency heating. An exothermic reaction takes place in which silicon chromate is formed and metallic cesium is released.

Although microphonic problems are not common in phototubes, it is sometimes important to prevent the introduction of a modulated current caused by relative movement of the elements of the phototube. Special beads and "snubbers" are sometimes introduced for this purpose and metal parts are usually spot-welded together.

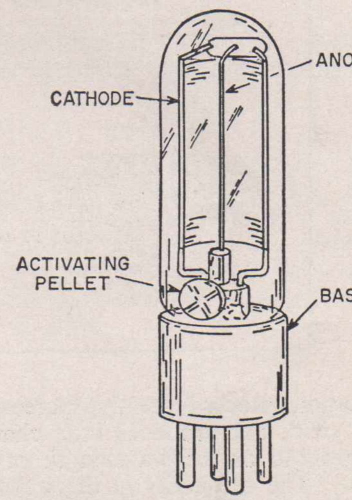



**Fig. 17—Typical construction of a vacuum phototube.**

# Properties of Vacuum Phototubes

## Spectral Response

The spectral response of a vacuum phototube depends upon the photocathode material and the spectral tranmission of the bulb window. Although pure metals have photoemissive properties, their response is usually rather poor and predominantly in the ultraviolet region; for most practical purposes, therefore, pure metallic photocathodes are of little value. Useable sensitivity has been obtained only with surfaces involving alkali metals. One of the first photoelectric surfaces to be used commercially was potassium sensitized with hydrogen. This type of surface is produced by the evaporation of a thin layer of potassium in vacuum. The surface is sensitized by exposing it to a glow discharge in a hydrogen atmosphere to form a surface layer of potassium hydride, which is presumed to be covered with a potassium film. The resultant surface may be symbolically represented as (K) — KH — K.[2]

TABLE VII

Expansion Coefficients for Common Glasses and Materials Used in the Manufacture of Phototubes

| | | Coefficient of Expansion $\times 10^{-7}$ (per °C) |
|---|---|---|
| **Soft Glasses** | | |
| 0080 | | 92 |
| 0120 | | 89 |
| 7285* | | 95 |
| *Radioactivity less than 10 cpm/kilogram | | |
| **Hard Glasses** | | |
| 7040 | | 47 |
| 7052 | | 46 |
| 7720 (Nonex) | | 36 |
| 7740 (Pyrex) | | 32 |
| 7750 | | 41 |
| 9741 | | 39 |
| **Quartz** | | |
| 7912 (Vycor) | | 8 |
| **Lithium Fluoride** | | 400 |
| **Sapphire** | Temperature - °C | |
| Parallel to C-axis | 50 | 666 |
| | 500 | 833 |
| | 1000 | 903 |
| Perpendicular to C-axis | 50 | 50 |
| | 500 | 77 |
| | 1000 | 831 |
| **Metals** | Temperature Range - °C | |
| Tungsten | 0 — 500 | 46 |
| Molybdenum | 25 — 500 | 55 |
| Nickel-Iron (42 alloy) 42 per cent Ni | 20 — 400 | 53 |
| Nickel-Iron (52 Alloy) 50 per cent Ni | 30 — 310 | 95 |
| Kovar | 25 — 300 | 60 |
| Platinum | 25— 100 | 91 |
| Chrome Iron | 25 — 500 | 108 |
| Dumet | | 92 radial<br>65 axial |

This sensitization process greatly increases the photoelectric yield, but produces little change in either the threshold or the wavelength of maximum response. The sensitivity at the wavelength of maximum response, 4400 angstroms, has been reported as high as 0.023 ampere per watt (about 7-per-cent quantum efficiency). However, as shown in Fig. 18, the spectral response is so limited (especially for applications involving tungsten lamps) that the surface is not generally used for commercial applications.

The silver-oxygen-cesium photo-cathode (used in tubes having S-1 response) is more important commercially because it is more sensitive to long wavelengths than the potassium-hydride photocathode. Commercial photocathodes of this type are prepared by oxidizing a porous silver base in an oxygen glow discharge to a degree determined by the appearance of interference colors at the surface. Cesium is then introduced and the surface is baked at about 250 degrees centigrade until a characteristic straw color results. Maximum sensitivity at the 8000-angstrom peak corresponds to only about 0.8-per-cent quantum efficiency, but the spectral range is wide. In addition, this type of photo-cathode can tolerate a somewhat higher ambient temperature (100 degrees centigrade maximum) than most photocathodes.

A closely related photocathode in which rubidium replaces cesium is used in tubes having a spectral-response characteristic identified as S-3. Although the sensitivity of this surface is not high, it has proved useful in color-matching applications.

The most important photocathode currently used in vacuum phototubes is the cesium-antimony "alloy" surface developed by Goerlich.[3] In the formation of this photocathode, an evaporated layer of antimony is treated with cesium vapor at 170 degrees centigrade. The resulting photo-

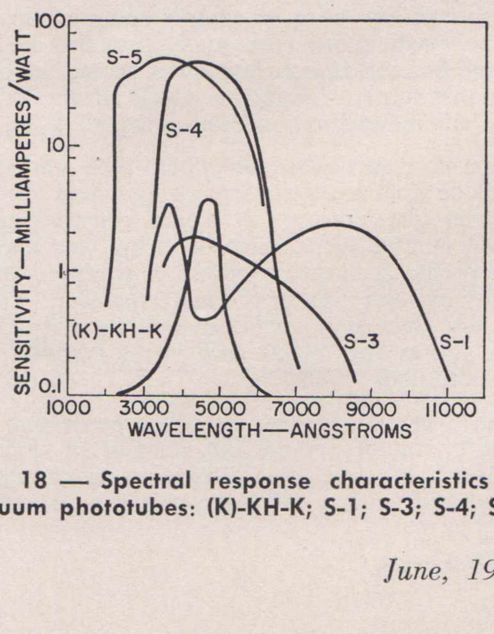



**Fig. 18 — Spectral response characteristics of vacuum phototubes: (K)-KH-K; S-1; S-3; S-4; S-5.**

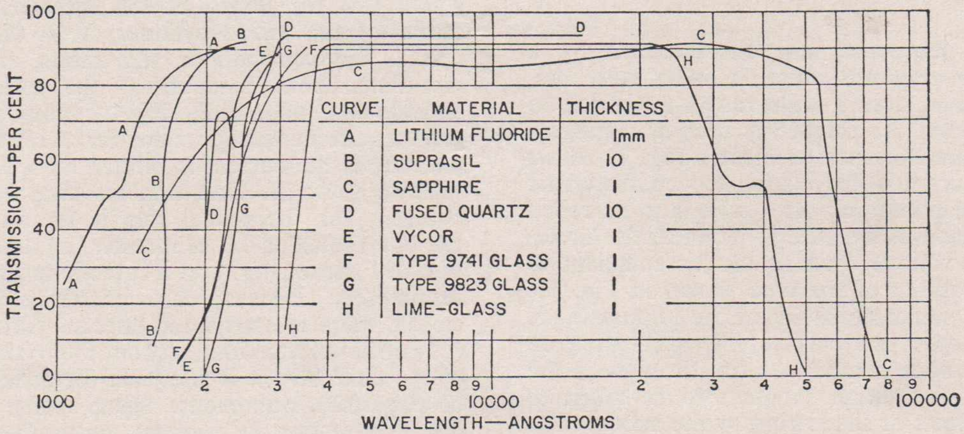



**Fig. 19—Transmission characteristics of various glasses used in phototube manufacture.**

cathode, which is believed to be a semiconductor $Cs_3Sb$,[4] is characterized by high sensitivity in the visible spectrum. The spectral response for the cesium-antimony surface deposited on a solid backing mounted in a lime-glass bulb is shown in Fig. 18; it is identified as S-4. Quantum efficiency is occasionally as high as 31 per cent at 4000 angstroms, the wavelength of peak response.

The envelopes of most phototubes are made of Corning 0080 lime glass, which cuts off transmitted radiation in the ultraviolet region at about 3000 angstroms. Envelopes have also been made of ultraviolet-transmitting Corning 9741 glass. A cesium-antimony cathode having the latter type of window provides the spectral response identified as S-5 in Fig. 18. Some special phototubes have fused-silica windows, which further extend the spectral response in the ultraviolet region.

Transmission curves of several glasses used in phototube manufacture as shown in Fig. 19. These curves are for a typical thickness of 1 millimeter, except as noted; ultra-violet cutoff is critically dependent on the thickness of the glass.

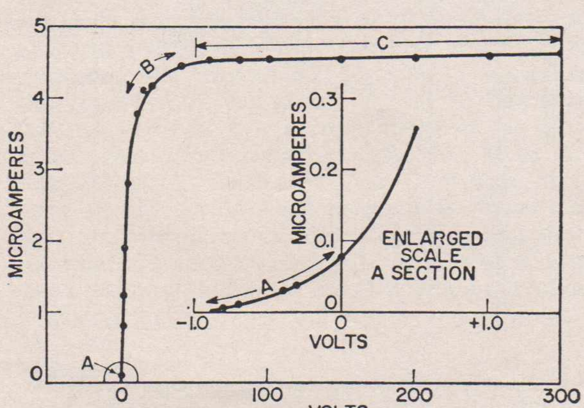



**Fig. 20—Current-voltage characteristic for a typical vacuum phototube showing the various regions of interest.**

The transmittance T of glass at a particular wavelength is described by the following relationship:

$$T = K10^{-\beta t} \qquad (20)$$

where K is a factor (approximately 0.9) dependent upon the surface reflectivity, $\beta$ is the coefficient of absorption, and **t** is the thickness. Near the cutoff wavelength it is important to use as thin a glass as practicable. Some experimental phototubes have windows made of a thin inverted bubble of glass.

## Current-Voltage Characteristics

A typical current-voltage characteristic for a vacuum phototube is shown in Fig. 20. At the foot of the curve (region A), the energy of the photoelectrons is sufficient to permit some collection by the anode, even against an opposing field. As the voltage is increased in the positive direction (region B), more of the emitted electrons are collected. However, because of the finite size of the anode, some of the electrons which escape and strike the bulb are lost to the output circuit. In the normal operating range (region C), the increase in current (approximately 5 per cent) is caused by a number of factors. Some of the increase is the result of improved collection efficiency at higher voltage. Photoemission is also slightly increased as a result of the applied electric field at the cathode, which aids in the emission by reducing the voltage barrier at the surface associated with the photoelectric work function. The increase in emission from this field effect is primarily observed in the neighbourhood of the long-wavelength cutoff of the spectral characteristic. Therefore, a phototube operated at a higher voltage is slightly more red-sensitive. In some phototubes, the vacuum may not be sufficiently low to prevent all ionization; this condition usually results in an increased slope of the current-voltage characteristic in the C range.

## Linearity

Vacuum phototubes are characterized by a photocurrent response which is linear with incident light level over a wide range—so much so that these tubes are frequently used as standards in light-comparison measurements. Fig. 21 shows the linear current-light relationship characteristic of a vacuum phototube. If a tube is to be relied upon as a standard because of its linearity characteristic, the voltage used should be sufficient to prevent instability of the type shown in Fig. 16. Because the photosensitivity of the photocathode may vary across the surface, the same area on the photocathode should be used throughout the measurement. Caution should also be taken to avoid the effects of shadowing by the anode. The anode should either always occupy the same relative area in the light beam, or the shadow effects should be avoided by placing the light beam to one side.

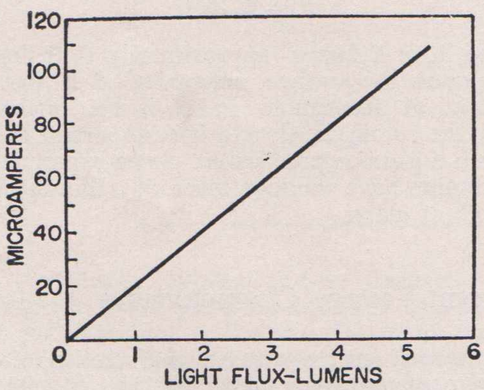



**Fig. 21—The linearity of current as a function of light for a vacuum phototube.**

Two effects may limit the linear operation of the phototube at high light levels, fatigue and space charge. At high current levels (recommended absolute-maximum current ratings are listed in the Phototube Data section) the tube may suffer both temporary and permanent fatigue, resulting from a change in surface composition. Because such fatigue is usually a function of both current and time, phototubes can often be used safely at very high light levels if the exposure is brief. The use of pulsed light makes it possible to develop large photocurrents (up to the point where the space charge limits the output current) without excessive fatigue effects.

The problem of currents limited by space charge between coaxial cylinders has been worked out by Langmuir and Blodgett.[5] In practical units, the expression for the current I in amperes per unit length l of axis is given by

$$\frac{I}{l} = \frac{14{\cdot}66 \times 10^{-6}\, V^{3/2}}{r\beta^2} \qquad (21)$$

where l is the length of the cylinder, r is the radius of the anode cylinder, V is the applied voltage between cathode and anode, and $\beta$ is a non-dimensional function of the ratio of the cathode and anode radii. Fig. 22 shows an experimental current-voltage curve for a 1P39 vacuum phototube; the current is plotted on a 2/3-power scale to show the limitation resulting from space charge. The theoretical line is for an assumed cathode radius of 0.8 centimeter, an anode radius of 0.051 centimeter, and a cathode length of 2.22 centimeters. Because the cylinder is only half closed, there are large end effects. Although Eq. (21) does not take into account the initial velocity of the electrons, it is adequate for general order-of-magnitude evaluations. Space charge is usually not a limitation in vacuum phototubes because steady currents of the magnitude necessary to produce space-charge limitation would usually first produce severe fatigue limitation.

## Frequency Response

The inherent response time of a vacuum phototube is exceedingly short. No time delay between the incidence of light and the emission of electrons has been measured.[6] For a vacuum phototube such as the 1P39 (anode radius of 0.051 centimeter, cathode radius of 0.8 centimeter) with an applied potential of 100 volts, the transit time for

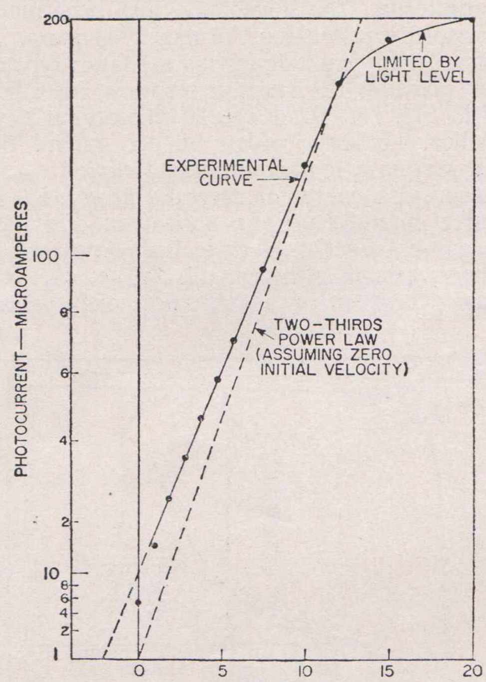



**Fig. 22—Experimental current-voltage curve for a 1P39 taken at high values of current to show the space-charge limitation. Note that the current scale is drawn on a two-thirds power scale so that the space-charge law becomes a straight line.**

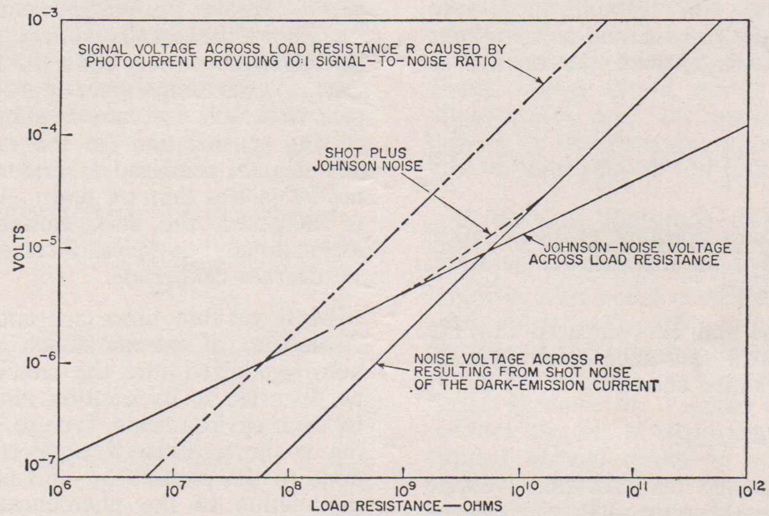



**Fig. 23—Variation of signal voltage, Johnson-noise voltage, and shot-noise voltage developed across the load resistor by the dark emission—all as a function of the load resistor. Data are for a vacuum phototube having S-1 response, dark emission of 10 picoamperes, and temperature of 300° K, and and for a bandwidth of 1 cycle.**

an electron having an initial velocity of zero has been calculated to be $3.9 \times 10^{-9}$ seconds (3.9 nanoseconds). The transit time itself does not limit frequency response; rather it is limited by the spread in transit time resulting from differences in initial electron velocities. For an electron energy of 1 volt and emission velocity directed toward the anode, the transit time for an applied potential of 100 volts is 3.3 nanoseconds. Thus, a total spread in transit time of approximately 0.6 nanosecond may be expected.

Although the calculation indicates that vacuum phototubes may theoretically be used at light-modulation frequencies approaching $10^9$ cycles per second (one gigacycle) practical difficulties preclude the realization of such performance. For example, the 1P39 has an interelectrode capacitance of 2.6 picofarads and its associated circuit further adds to this value; the total capacitance is approximately a minimum of 10 picofarads. In order that the circuit time constant not limit the response, the equivalent resistant - capacitance time constant of the circuit should be less than 0.6 nanosecond. For a capacitance of 10 picofarads, the load impedance would have to be less than 60 ohms. Unless the light level were high, such operation would not be possible. Nevertheless, for light pulses of high magnitude and short duration, the vacuum phototube is capable of very short response time when coupled with a minimum load resistance.

## Noise

As the light level and the photocurrent become less, it becomes difficult to distinguish the photocurrent from the dark current (current resulting from sources other than radiant flux on the photocathode). One limit of detection is in the fluctuation of the dark current, or dark noise.

Dark currents in vacuum phototubes arise from various sources. When both the anode and cathode are terminated in a base attached to one end of the tube, the leakage across the base may be a major source of dark current. Such leakage is particularly troublesome in an atmosphere having high humidity, especially if the base of the tube is dirty. In a vacuum phototube, internal electrical leakage usually results from excess photocathode activating material. Tubes having anode and cathode terminations at opposite ends of the tube, especially when the separation is also maintained inside the envelope, have a minimum of electrical leakage.

In such phototubes, the main source of dark current may be dark emission of electrons from the photocathode. Dark noise in the vacuum phototube is shot noise caused by such random dark emission. The rms fluctuation current in such cases is given by the following shot-noise relationship:

$$\overline{I^2_{\triangle f}}^{\,1/2} = \left[2e\, i_d \triangle f\right]^{1/2} \qquad (22)$$

where $i_d$ is the dark emission current, e is the electron charge ($1.6 \times 10^{-19}$ coulombs), and $\triangle f$ is the bandpass of the measuring circuit. When the signal current is just equal to this rms fluctuation current, the condition is that of minimum signal detection.

This minimum signal detection is rarely realized in vacuum phototubes. The noise associated with the dark emission is usually very small compared with the circuit noise. For example, for a load resistor of value R, the rms-thermal-noise voltage (Johnson noise) associated with the resistor is given as follows:

$$\overline{V^2_{\triangle f}}^{1/2} = \left[4\ kTR\ \triangle f\right]^{1/2} \qquad (23)$$

where k is Boltzmann's constant ($1.38 \times 10^{-23}$ Joule per degree), T is the absolute temperature, and $\triangle f$ is the bandpass.

The Johnson noise may be compared with the voltage across the lead resistance resulting from the fluctuating shot-noise current:

$$R(2e\ i_d \triangle f)^{1/2}.$$

The signal voltage and the shot-noise voltage across R both increase directly as R, whereas the Johnson noise voltage increases only as the square root of R.

Consequently, if the load resistance is made sufficiently high, the signal-to-noise ratio from the circuit improves until the limitation resulting from shot noise alone is reached (see Fig. 23). The resistance R for which the two noise sources are equal may be determined as follows:

$$R(2e\ i_d \triangle f)^{1/2} = (4kTR \triangle f)^{1/2}$$

or

$$R = \frac{2\ kT}{e\ i_d} \qquad (24)$$

For example, for a vacuum phototube having S-1 response and total dark emission of $10^{-11}$ ampere (10 picoamperes) at room temperature, the value of R from Eq. (24) is 5000 megohms. For tubes having lower dark emission, such as those with S-4 response, the value of load resistance which must be exceeded to override Johnson noise becomes orders of magnitude above practicability. Even with a 5000-megohm load resistance, the time constant of the circuit limits the response to only a few cycles per second. For applications requiring detection of very low light levels with high-frequency response, it is advisable to use a multiplier phototube.

### Environmental Factors

As a rule, the sensitivity of a vacuum phototube is only slightly affected by the ambient temperature. However, a small reversible effect may be observed in the spectral range near the long-wavelength cutoff where increasing the temperature tends to increase the wavelength for cutoff. Permanent changes may result from redistribution of the sensitizing metals at elevated temperatures.

Most phototubes are rated to a maximum temperature in the range of 75 to 100 degrees centigrade. Above the maximum rated temperature, the phototube usually suffers permanent loss of sensitivity depending upon the length of exposure time. As the temperature approaches the temperature to which the tube is subjected during processing sensitization (in the range from 150 to 250 degrees centigrade), serious loss of sensitivity occurs in less than an hour. As the temperature is increased, the dark emission also increases exponentially; a typical increase is 2:1 for every 10 degrees centigrade.

Most vacuum tubes are not designed for environments of extreme shock or vibration. In a nonruggednized tube, the cathode would probably be distorted in its position relative to the anode by such environments, even to the extent of causing a short. Even if no permanent damage is done to the phototube, difficulty may arise from modulation of the photocurrent resulting from vibration of the photocathode in the beam of light because different areas of the photocathodes may have different sensitivities. A typical variation in cathode sensitivity (sometimes resulting from the heat used to seal the bulb to the stem) is from low sensitivity near the stem to high sensitivity at the upper end of the cathode.

Under normal operating conditions, the vacuum phototube is one of the most stable photosensitive devices available. When stored in the dark at normal temperatures and operated at low photocurrents, vacuum phototubes can be used as a reasonably good laboratory standard. They usually show a loss in sensitivity during continuous operation, depending upon the magnitude of the current. Fig. 24 shows typical life characteristics of vacuum phototubes having S-4 and S-1 spectral responses for continuous operation under the test condition.

Most vacuum phototubes are rated to several hundred volts; normally there is no need for higher voltages. Spacings of the leads in the stem and base are not designed for very high voltages which would cause arc-overs, usually across the base. For best operation, high temperatures, high humidity, high voltage, dirty or greasy environments, and excessive vibration or shock should be avoided.

## Application Considerations

Vacuum phototubes are used to best advantage in applications which exploit their stability, good frequency response, flat current-voltage characteristic, and linearity of photocurrent with radiant flux.

In applications requiring the observation of light pulses of short duration, or light modulated at relatively high frequencies, the vacuum phototube performs better than gas-filled phototubes or most solid-state photocells. Because vacuum phototubes are relatively stable over long periods, they may be used as standards of reference or in applications requiring long periods of operation without recalibration. The vacuum phototube, because of its linear characteristic, may be used in many applications as an instrument for measuring light flux.

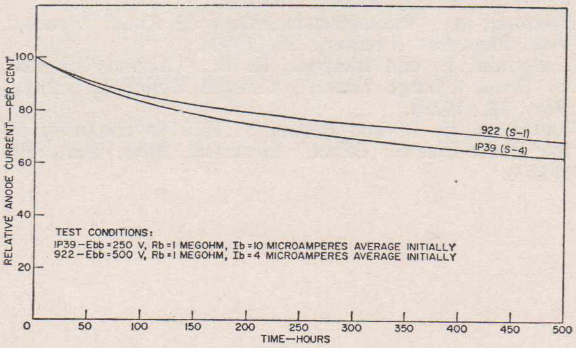



**Fig. 24—Typical life characteristics for two types of phototubes having S-4 and S-1 spectral-response characteristics.**

The maximum ratings provided in the data for vacuum phototubes should be carefully adhered to, especially in commercial applications in which many tubes are used in identical circuits. In laboratory applications, however, it is possible to exceed published ratings if the experimenter takes into consideration the behaviour of the device and the reasons for the stated limitations. The minimum dc load resistance value shown in the data for each type is recommended to prevent damage to associated circuit components in the event of a short circuit in the phototube, which normally serves as a high series resistance.

The voltage supply for a vacuum phototube is not critical because of the flat current-voltage characteristic. A minimum of approximately 20 volts is usually recommended for most phototubes to provide an adequate collection field, although more than 100 volts may be desirable to prevent bulb charging caused by initial electron velocities. Voltages higher than the maximum rating (usually around 250 volts) should not be used because they may result in electrical breakdown between external elements of the tube.

Usually, the life of a vacuum phototube (for a given decrease in sensitivity) is related approximately inversely to the current drawn through the tube. More stable and reliable performance results if small areas of concentrated illumination on the cathode surface are avoided.

Phototubes should not be stored in light when not in use. Blue and ultraviolet light especially can cause photochemical changes in the cathode which result in changes in sensitivity. It is especially important to avoid exposure to intense illumination such as sunlight even when no voltage is applied to the tube. Permanent damage may result if the tube is exposed to light so intense that it causes excessive heating of the cathode. Tubes should not be stored for long periods at temperatures near the maximum rating of the tube; high temperatures almost always result in loss of sensitivity of the tube.

A vacuum phototube may be operated with either dc or ac applied voltage. Usually a dc supply is preferred, especially for measurements involving very small currents. However, in some applications an ac supply can be used to advantage because of the time relationship provided; the ac supply may also be less expensive in some applications. Because the vacuum phototube acts as a rectifier, the use of steady illumination and an ac applied voltage results in approximately square waves of unidirectional current flow. In this case, a dc current meter would indicate an average current approximately half that indicated when a dc power supply is used.

Whenever a small ac signal from the phototube is to be observed and the amplifier gain is high or the load resistance is large, it is recommended that shielding be provided for the phototube and the signal output loads. It is advisable to make the signal lead as short as possible to avoid pickup and stray capacitance. This precaution is important if frequency response is a consideration. Because a phototube is a high-resistance device, it is important that insulation of associated circuit parts and wiring be adequate. In very critical applications it may be desirable to use a phototube in which the signal lead (either anode or cathode depending upon polarity of signal desired) is terminated through an insulated bulb-top cap. The power supply should be connected between ground and the phototube element not used for signal output to avoid unnecessary pickup of extraneous signals.

For maximum sensitivity of phototube circuits, leakage resistance of circuit parts and wiring insulation should be high. Leakage across moisture films on the surface of the glass can be prevented by coating the glass with pure white ceresine wax, silicones, or other non-hygroscopic insulators. For example, in the case of a tube having a top-cap connection, a continuous band of wax approximately a half-inch wide around the top cap or around the bulb is sufficient to interrupt all external leakage paths.

Some phototubes have special nonhygroscopic bases which provide a substantial advantage in critical applications; special sockets can also be obtained which minimize leakage in humid conditions. Teflon is one of the best materials for such sockets.

In many applications, it is advantageous to modulate the light flux which is to be detected by the phototube. Modulation can be achieved in a variety of ways: the most common method is the use of a rotating disk or "chopper" which has a number of holes that modulate the light beam; other methods use a vibrating reed or diaphragm, rotating mirrors, or a Kerr cell.

Undesirable modulation may occur if vibration of the phototube causes a shift in the position of the light spot on the photocathode because the photosurface may not be uniformly sensitive or because the anode may interrupt more or less of the light. In general, it is desirable to use a large spot of light on the photocathode to minimize microphonic effects and cathode current density.

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