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SURVEY OF VACUUM PHOTOTUBES

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SURVEY OF VACUUM PHOTOTUBES

by Yu. Luk'yanov

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1. Introduction

The advances gained in the development and study of new cathodes have been one of the leading factors in the overall progress of electric vacuum engineering over the last two decades. For example, the excellent parameters of present-day radio tubes are linked to a large extent with improvements in the technology of ~~oxide cathodes~~ barium oxide cathodes. ~~A~~ A fully valid solution to a number of problems in the technical application of secondary emission has only proved possible since the discovery of cathodes

possessing a high coefficient of secondary emission. Finally, the rapid development of a sphere of special interest to us - photoelectric engineering - in particular, the construction of modern, highly sensitive phototubes, iconoscopes and electronic-optical image converters has also only proved possible since the invention in 1930 of the oxygen-cesium cathode, and in 1936 of the antimony-cesium cathode. Both these complex cathodes constitute considerable physical interest, apart from their importance in engineering, by dint of a number of characteristic features, and further study and improvement of them has so far been one of the most topical problems of electronic engineering.

In terms of vacuum phototubes the application of new cathodes has meant:

1. An increase in integral sensitivity by a factor of about 30. Indeed, instead of phototubes with a sulphur-potassium cathode, the sensitivity of which was only 3 or 4 μA/lm, we now possess oxygen-sensitized antimony-cesium cathodes with a sensitivity attaining 120 - 140 μA/lm.

2. A wider spectral region recordable by means of the phototubes. Whereas before the photo-active surfaces were only highly sensitive in the ultra-violet and blue-green regions of the spectrum, at the present time, in addition to a sharp increase in sensitivity in the blue-green region (antimony-cesium cathode), there have been constructed surfaces possessing high sensitivity in the red and infra red regions of the spectrum (modifications of the oxygen-cesium cathode).

3. Major progress has been attained in increasing the service life of phototubes. For example, the introduction of phototubes containing antimony-cesium cathodes has made it possible to step-up the guaranteed service life of commercially-produced standard products to a thousand hours, and that is still not the limit. Over the period in question, the temperature stability of phototubes has also been substantially increased.

The principle spheres of application of phototubes and photo-electric

instruments over the last 10 or 12 years has been:

1. Talking motion pictures.
2. Television and phototelegraphy.
3. Industrial and military telemechanics.
4. Objective photometry, colorimetry and pyrometry.

But both in the qualitative and quantitative respect these fields have changed completely, largely through improvement in the phototube, i.e., increased sensitivity and stability during operation. The phenomenal spread of the sound cinema and the ever-growing use of phototubes in industry has in turn been an incentive for the construction of standard and portable instruments. As a result, there has been a transition from the more primitive laboratory production to mass production of phototubes with standard parameters, that are cheap and reliable. In view of the overall tendency towards standardized products characteristic of the period in question, the pointlessness of gas filled phototubes, unstable in service and subject to inertia, becomes increasingly clear[1]. Indeed, the extremely limited gain in sensitivity from gas-filled phototubes has no longer been necessary in any of the fields in which phototubes are used on a wide scale since the invention of the high sensitivity antimony-cesium tube and the progress made in modern amplification techniques. This relates first and foremost to the very important sphere of application of phototubes - sound motion pictures. Thus, with rare exceptions vacuum phototubes predominate in modern engineering.[2]

One more important fact should be pointed out in connection with the introduction of antimony-cesium phototubes. The comparatively high work function characteristic of the antimony-cesium cathode results in a very small thermal electronic emision - about 10^{-13} A/cm^2 at room temperature. This quantity, being about two orders below the figure for the oxygen-cesium cathode, reduces the ratio between the useful signal and the noise level and makes it possible to employ a higher amplification

factor, making antimony-cesium phototubes splendid low-illumination indicators.

The aim of the present paper is to describe the properties of present-day vacuum phototubes. At the beginning of our article, we give a description of the procedure for manufacturing phototubes with complex cathodes and consider the principal designs for them (Sections 2 and 3). The remainder of the paper (Sections 4 and 5) deals with the luminous and electric characteristics of phototubes. At the end (Section 6) we briefly consider the application of phototubes and give basic reference data for commercial production, after which follows a bibliography.

2. Technological procedure for manufacturing phototubes

a) General comments

Modern phototubes make use of composite photocathodes containing the alkaline metal cesium. Phototubes of this kind are therefore high-vacuum glas containers inside which is placed a photocathode, either coated on the inside surface of the glass or on a metal plate. In front of the cathode is the anode which collects the photo-electrons; the shape and size of the anode has to be selected in such a way as to prevent free access of the light to the surface of the cathode. The metallic and glass parts of the instrument must satisfy a number of requirements, which we will consider in brief[3].

The most important properties which have to be taken into account when selecting a type of glass for making phototubes are as follows: 1) the optical transparence of the glass to rays in a given region of the spectrum; 2) the chemical stability of the glass.

The normal types of glass used in electric vacuum production and manufactured by Soviet industry (types 23 and 46 made by the Druzhnaya Gorka Plant, and types 16, 35 and 58 made by the Moscow Glass Works) effectively transmit visible and close infra red rays (up to 3 or 4 μ), but are almost opaque to ultra violet light, even with

wavelengths 3000 - 3500 Å. Hence these types of glass are unsuitable for making phototubes intended for recording ultra violet light; in such cases we have to use special uviol glass ~~which is~~ distinguished from ordinary glass by the almost complete absence of iron impurities, which in ordinary glass are present on account of the high absorption of them in the ultra violet region. The limit of transparency for uviol glass lies at about 2400 Å. For working in a more distant ultra-violet region use can be made of quartz glass (transmission factor 90 - 98% right up to 1800 Å). From the chemical point of view the above-mentioned types of glass are extremely stable, dissolving only in hydrofluoric acid; it is only "lead" glass (type 16), containing lead oxide that reacts with the vapor of alkaline metals at high temperatures and becomes opaque to incident light.

The commonest materials used to make leads are platinum (or platinite) and molybdenum, which can be effectively welded to glass 23 and 58, or 35 and 46, respectively. Some parts of the inside fittings of the phototube - the anode, anode traverse and cathode - are made of nickel, which is soldered to the platinite or molybdenum electrode passing through the glass by means of spot welding. The use of nickel is extremely convenient since it does not oxidize when kept in air and its surface can be comparatively easily cleaned and degassed to a high degree.

Just before they are welded to the cylinder, the metal parts in the phototube must be cleaned free of dirt, for which purpose they are washed in an organic solvent to remove ~~this~~ grease, and then annealed in a vacuum in hydrogen. During mass production the parts are procured and cleaned beforehand and then kept in the clean state in sealed glass jars.

A typical vacuum system used for the manufacture of phototubes is shown in Fig. 1. The prevacuum pump is marked 1, a three-way tap connects it to a glass or metal Langmuir pump, 3, working on mercury vapor or apieson oil vapor. The use of

two-stage fractioning oil pumps that do not need water cooling is particularly useful. By means of as short and wide a pipe as possible, the high vacuum pump is joined to the header,4,to which the phototubes being evacuated are soldered;the arrangement of the header and tubes permits them to be placed in a furnace for heating, which is necessary to degas the glass. Two branches are soldered to the connecting pipe between the three-way tap,5,and the simple tap,6;one of them,7,is joined to a low-pressure manometer,while the other,8,is used to lead in pure dry oxygen(obtained by the decomposition of $KMnO_4$,or another gas)into the system,if required for the manufacture of the cathode. Right in front of the header and behind the last tap,6,is a liquid air trap. The connecting pipe, 11,makes it possible to pump out the system,bypassing the hihg-vaccuum pump which is switched off in the process. The high-vacuum pump which is switched off in the process. The high-vacuum pump is switched into the working position by turning the three-way taps, 2 and 5,and evacuates the gas residue from the system.

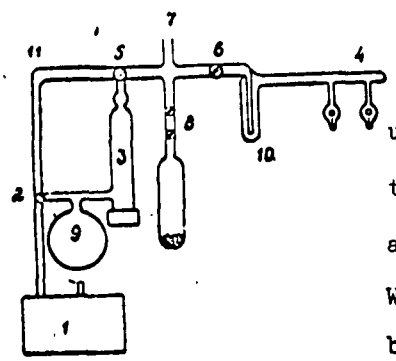

Fig. 1

b) Manufacture of oxygen-cesium photocathode

At the present time there are two commonly used procedures for manufacturing oxygen-cesium cathodes. The first of them /23,31,36/ is usually used when a silver plate is used as the backing;it is widely employed in the United States(RCA Westinghouse). The second version /30/is used when the silver backing is chemically applied to the glass walls of the photo tube bulb. This method is used in the Soviet Union(Kuybyshev Electrical Works in Moscow)and in Germany(Pressler,AEG,Telefunken). Let us deal first with the first version.

Oxygen-cesium phototubes with a plate employ a cathode made of thin silver foil or electrolytically silver-plated copper rolled into a semi-cylindrical surface;in front of the cathode,along the axis of the cylinder is a nickel anode in the form of a straight wire. When the base of the phototube has been assembled, it is welded to a cylindrical glass bulb with two openings; the first is for evacuating

the phototube and the second is for welding on an ampoule containing the cesium salt and reducing metal in a nickel capsule. The capsule is often mounted inside the phototube; there is then no need for the second unsoldered opening.

The main stages in manufacturing oxygen-cesium phototubes are as follows:

1. preparatory operations and bending of the silver backing;
2. oxidation of the silver surface;
3. production of the cesium from the chemical compound;
4. activation of the cathode.

Operations 2 and 3 are the same for both manufacturing techniques, the first and fourth differ rather considerably.

Let us first consider the sequence in operations for the first technique.

1. Bending

The phototube, having been soldered to the vacuum system, first undergoes normal heating in a furnace (one hour at 400° C) to degas the glass; in the process the trap is cooled by liquid air and maintained in the cool state until the finished phototube is unsoldered from the vacuum system. The silver backing, despite preliminary cleaning, never has a completely homogeneous surface, hence the oxidation of it by means of a glow discharge does not produce a sufficiently even layer of oxide the first time. This fact plus the desire to produce as rough, branched and at the same time standard cathode surface as possible, makes it necessary to preface oxidation of the plate by "bending" it. Considerable roughness of the surface enables us to obtain a cathode with greater sensitivity. To bend the cathode pure dry oxygen at a pressure of about 1 mm Hg is led into the phototube and a brief glow discharge from a voltage source 800 - 1000 V is passed through the tube; the discharge current should be of the order of several milliamps. The circuit shown in Fig. 2 can conveniently be used for the bending operation; here the switch K_1 is put in a central

position while the key K_2 keeps closing every so often. During the bending operation the silver plate is the cathode and is rapidly oxidized while bombarded by positive ions; the oxidation can be judged from the appearance of interference colors(temper colors) on it. As soon as the number of bright hues have passed, the plate becomes completely black and dull; the thickness of the oxide layer is several thougand molecular layers/36/. When this state has been attained,the oxygen pressure in the phototube is increased to several mm Hg and key K_2 is closed for a longer period. The heat generated during the discharge causes dissociation of the silver oxide,and the plate reacquires its white color. As soon as the first portion of oxygen has been pumped out and the new portion pumped in,the process is repeated several times until the plate acquires smooth dull white surface and the oxidation begins to take place completely uniformly and without spots. If the cathode has been made by electrolytic silver plating,the bending operation inside the evacuated phototube can be discarded since a standard,clean and duly rough surface can be obtained during the actual electrolysis by carefully selecting the density and duration of the current.

2. Oxidation

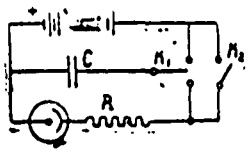

Fig. 2

Oxidation of the cathode is an extremely important operation; the proper choice of the thickness of the oxide layer is of primary importance in repeatedly obtaining high-grade cathodes. The optimum amount of oxygen calculated per 1 cm^2 of the geometric silver surface is approximately 4 micrograms/3,36/which in terms of molecular outside alyers is β80 molecular layers(on the assumption that the cathode surface is ideally smooth). An idea of the thickness of the oxide layer can conveniently be gained from the above-mentioned change in color of the cathode when the glow discharge is passed through it. The sequence of the colors as the thickness of the film increases is as follows: yellow,red,violet,blue,green,yellow again, and so on. The above-mentioned optimum thickness corresponds to a yellow-green color.

Since the silver oxidizes very rapidly, for a stricter and more accurate proportioning of the absorbed oxygen it is best to use the key K_2 (Fig. 2), the switching of which from the top to the bottom position is accompanied by the discharging of the large capacitor C($\sim$ 6μF) through the phototube; each individual discharge causes an extremely slight degree of oxidation; the pressure of the oxygen during oxidation is taken as equal to 1 mm Hg.

3. Obtaining cesium

When the oxidation of the surface has been completed and the oxygen has been pumped out, we begin making the cesium metal; to do this the nickel capsule containing a cesium salt and a reducer is made incandescent with high frequency currents. There are two commonly used methods of obtaining the cesium metal - the chloride and thermite methods. In the first case, use is made of a mixture of cesium chloride and calcium metal filings; the amount of Ca has to be in excess of the amount required for stoichiometric proportions. In the thermite method use is made of cesium dichromate and powdered aluminum. Six parts Al are taken to nine parts $Cs_2Cr_2O_7$ by weight; since the reaction is a violent one, a "diluent" - chromium oxide (Cr_2O_3) or aluminum oxide (Al_2O_3) - is often added. On the basis of this amount of absorbed oxygen, it is easy to calculate that to reduce all the silver oxide formed we have to have about 65 micrograms of cesium metal per 1 cm^2 of cathode surface. In practice the initial materials are taken in a proportion ensuring an approximately threefold margin of pure Cs (about 200 $\mu g/cm^2$). The cesium produced when the capsule is heated is in the form of vapor which condenses on the cold walls of the ampoule or bulb of the phototube. If the cesium is obtained in a lateral ampoule, it is distilled inside the tube which is then placed in a furnace for activation.

4. Activation

During activation the silver oxide is reduced by the cesium as follows

$$Ag_2O + 2Cs \longrightarrow Cs_2O + 2Ag$$

and the surface is coated concurrently by adsorbed cesium atoms. Some of the cesium atoms diffuse inside the cathode, turning into internally adsorbed atoms. As a result we get a photocathode with a thick semiconducting layer on the surface, possessing a low work function and high photosensitivity. The activation process is carried out between 180 and 190° C and lasts about 20 minutes. During the process the photosensitivity of the cathode is gradually increased; by illuminating the cathode through the furnace window with an electric light and measuring the photocurrent produced with a needle-type galvanometer, a check can be kept on how the operation is proceeding. At the initial stages. while there are still considerable resources of metallic Cs in the phototube, high conductivity currents due to films of cesium settling on the base of the phototube may be superimposed on the photocurrent. As the heating continues, the excess Cs is partially evacuated into the vacuum system and partially absorbed by the cathode. When the photo-electronic and at the same time thermo-electronic emissions attain steady-state values, and the conductivity current vanishes, the activation of the cathode is complete, the furnace and phototube is removed and the tube is unsoldered from the vacuum system.

In the case of mass production, it is inconvenient and time consumming to treat each phototube individually during the activation operation. A different technique has therefore to be used in which an appropriate getter (for example, CuO, Pb_3O_4) is used to absorb the excess Cs. The process is then modified in the following way: as soon as the oxidation is over, the phototubes are unsoldered from the vacuum system,the capsules mounted inside the bulk are heated by high frequency current to reduce the cesium, and the phototubes, in batches of about several dozen,

are placed in a thermostat and heated to 190 - 200° C. During assembly of the phototube the getter is usually coated on the glass base in the form of a powder dissolved in water and throughout the activating operation absorbs the cesium[5]. Completion of the activation energy can easily be observed from the color of the activated surface; the finished cathode should be brown-gray in color; the activation time is about 10 minutes /23/.

Let us now discuss the second manufacturing technique. The silver on the glass is in this case obtained by chemical silver plating by the Brescher method[6]. To make certain the silver layer adheres to the glass it should be washed with a 1% solution of lead chloride $SnCl_2$. Phototubes with a cathode on the glass are usually spherical or cylindrical in shape; in the first case the anode is shaped like a wire ring and in the second case it is in the form of threads arranged along the axis of the bulb.

In this method of manufacturing the cathode, the silver backing is not bent, since the chemical silver plating operation when carried out by the standard method ensures identical backings with the necessary roughness. Hence the vacuum system is only used to carry out the following operations - oxidation of the silver, reduction of the Cs and activation of the cathode.

The oscillation comes after normal evacuation and degassing and is carried out in the way described above, except that the depth of oxidation is slightly less and corresponds to the dark blue surface color. The Cs metal is reduced after evacuation of the oxygen in the side ampoule and activation of the cathode then begins.

In the case in point the Cs is not distilled immediately inside the phototube bulb, since this leads to deterioration of the cathode, but is distilled slowly from the ampoule by heating the instrument up to 190° C. The chemical reaction within the cathode and the formation of the best coating by adsorbed atoms is checked by

careful and continuous observation of the thermal electronic cathode emission, which varies in parallel with the photo-electronic emission and is not disguised in the given case by conductivity currents because of the gradual admission of cesium. Fig. 3 shows a typical activation curve indicating the variation in thermal electronic emission as the phototube in the furnace is heated. As can be seen from the graph, the thermal electronic emission first builds up slowly, then more rapidly and attains a sharp peak, after which there is a very rapid decline. The peak is attained at the moment the surface is covered with an optimum coating corresponding to a minimum work function; the rapid fall beyond the peak is due to admission of new excess Cs atoms, so that the optimum state is already passed. At this time, the furnace and the phototube are removed and the ampoule is rapidly unsoldered. When this has been done, the thermal and photocurrents are low on account of the excess cesium on the surface. By carefully heating the tube again at 170 - 190° in the furnace, the excess can be removed and the optimum cathode structure is restored, as shown by a new increase in the thermal electronic emission. When the emission has reached its former value or an even higher value, the cathode heating is stopped and the phototube can be unsoldered from the system.

If we decrease the time taken by the silver plating or the concentration of the silver-plating solution when the glass is being silver-plated to make the photocathode backing, the initial coating may be semitransparent - and appear blue in color in transmitted light (light transmission factor about 20%). A backing of this kind is suitable for making semi-transparent cathodes used in a number of instruments (dissectors, image iconoscopes, light converters). This method of making the cathodes coincide basically with the one described. To ensure good contact the silver coating near the leads should be made thicker and low current should be used for the oxidation (a greater balast resistance is used - $R \sim 2 \cdot 10^5 \Omega$).

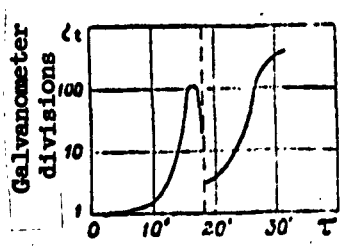

Fig. 3

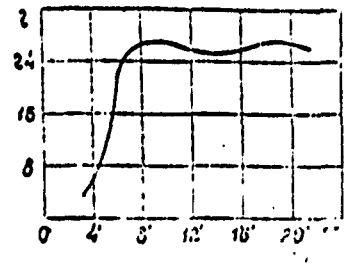

Fig. 4

The sensitivity of an oxygen-cesium cathode made by the above-described method may be increased further by evaporating several dozen atomic layers of silver metal/33, 41,42/ on the surface of a finished cathode, and then heating the phototube in a furnace at a temperature not above 150 °C for several minutes with continuous observation of the photocurrent. This treatment increases the sensitivity of the cathode by a factor of 2 or 3; the increase in the integral sensitivity of the cathode is accompanied by a variation in the spectral sensitivity curve(for more details see Section).

In comparing two methods of manufacturing oxygen-cesium phototubes, we should point out the following two facts.

1)When manufacturing photo-electric instruments in the laboratory,the second method provides cathodes with slightly greater sensitivity(even without the additional evaporation of the silver).

2) The first method provides more standard results;its advantages are considerable when the instruments are batch produced.

Let us now go on to consider the manufacture of antimony-cesium photo-cathodes.

c) Manufacture of antimony-cesium photocathodes

The manufacture of antimony-cesium phototubes is considerably simpler than for oxygen-cesium ones. It comprises the following stages:

1) Preparatory operations and coating with antimony metal.

2) Activation of the photocathode.

When making the normal phototube with a photo-active coating on the inside of the glass,a tungsten spiral is welded to two middle electrodes at the base of the phototube and a small antimony crystal is inserted in it. The assembled base is welded into a spherical bulb equipped with two unsoldered holes. The photocathode

is produced on the glass surface of the bulb and a platinum wire is used as its lead. The cesium salt and reducer are placed in a nickle capsule, which inserted in the side glass ampoule.

After evacuation and normal degassing of the glass bulb, the tungsten spiral is made incandescent by an electric current and the antimony sublimates onto the walls of the bulb. The thickness of the sublimated layer is determined roughly with the naked eye - the antimony coating should be a brilliant silver color and almost completely opaque to light (this corresponds to a thickness of about 1500 Å). By heating the bulb on one side with a burner we can make a window of the desired size to admit light inside the phototube. When the antimony has stopped vaporizing, the cesium in the ampoule is reduced and is immediately, in great excess, distilled inside the phototube and begins to activate the photocathode.

Activation is carried out by heating the phototube in a furnace at a temperature lying between 140 and 200° C (according to the thickness of the coating). The Cs atoms reaching the surface of the antomony react with it, forming a compound which is probably $SbCs_3$ /63/. The formation of this chemical compound is accompanied by a change in the appearance of the cathode; it becomes slightly transparent, acquiring a reddish tinge in transmitted light and a green tinge in reflected light. The increase in optic transluscence of the cathode is accompanied by an increase, averaging 10^5, in the longitudinal resistance of the coating, and the metal cathode becomes a semiconductor. The excess Cs atoms in the bulb not only convert the whole of the antimony into a compound, but also diffuse inside the layer. At the same time, the surface becomes coated with adsorbed atoms of Cs reducing the work function. The operation can be conveniently observed from the variation in photocurrent (measurement of thermo-electronic emission is inconvenient since it is small at the usual activation temperatures on account of the comparatively small work function of the

cathode. A typical curve showing variation in the photocurrent during activation is given in Fig. 4 /55/, the activation temperature was 185° C. As we can see, the photocurrent is quickly established; further heating of the cathode in cesium vapor does not alter the sensitivity. When the photocurrent obtains a steady-state value, and the excess cesium has been pumped into the vacuum system (this can be recognized from elimination of the conductivity current), heating of the phototube is ceased, and the activation can be considered finished. It should be pointed out that when making antimony-cesium phototubes, the problem of measuring the cesium portions is not so important as in the manufacture of oxygen-cesium phototubes. The excess cesium, which has a ruinous effect on the grade of oxygen-cesium cathodes on glass, is not dangerous in the given case and in order to remove it we need only continue heating the phototube in the furnace for a longer time.

By treating the surface of a finished antimony-cesium cathode with a small amount of oxygen, we can increase its sensitivity by a factor of 1-1/2 to 2. For this purpose oxygen is introduced into thephototube at a pressure of about 10^{-3} mm Hg. The immediate increase in sensitivity can be recorded with the same galvanometer that is being used to keep check on the activation process. The excess oxygen causes a reduction in the photocurrent; in this case to restore high sensitivity it is useful to heat the photocathode in the cesium vapor a second time.

In certain cases we need to make antimony-cesium cathodes with a metal plate. Here nickel with a pre-oxidized surface can be successfully used as the backing for the antimony coating.

3. Design of Phototubes

Among the large number of different designs possible in phototubes we can single out the following fundamental groups:

1) phototubes with a central anode;

2) phototubes with a central cathode;

3) phototubes with plane-parallel electrodes.

Phototubes of the first type are most often used in practical work; there are two common designs for this group of phototubes - spherical and cylindrical. Examples of the first designs are the above-described oxygen-cesium phototubes with the cathode on the inside of the glass, and the antimony-cesium phototubes. Examples of the second kind are phototubes with oxygen-cesium cathodes on a plate. In the electrical respect these phototubes are characterized by comparatively weal electric fields near the surface of the cathode; this results in high saturation potentials. These phototubes are convenient for intercepting wide beams of light on account of the large-size cathode, and, furthermore, in the case of the spherical tubes with a small window, the design of the tube is close to that of an absolutely black body and therefore results in almost entire absorption of the incident light luminous flux and this, in the case of a cathode with a good reflecting surface, may slightly improve the sensitivity. Figs. 5, 6 and 7 show different phototubes with a central anode. The spherical one (TsG-1), shown diagramatically in Fig. 5, is made by the Moscow Elektrozavod; the oxygen-cesium type cathode in this phototube is located on the glass; the cathode lead is closed by the cap, K while the anode lead is joined to the anode pin in the base. The weight and size of this phototube is fairly extensive (see below). A much more portable phototube (made by the same factory) is shown diagramatically in Fig. 6. It is the STSV-51 and possesses an antimony-cesium cathode; the tungsten spiral from which the antimony is vaporized is closed on one side by a nickel screen so that the window in the bulb is obtained automatically. The electrodes are led off from different sides of the bulb and enclosed in a metal base of cylindrical shape. In phototubes of this design, apart from a considerable gain in weight and size, we also find a reduction in the inter-electrode capacity and an increase in the insulation resistance between the electrodes. Another small and light phototube is the RCA-929 made by RCA /28/ which is cylindrical in shape and

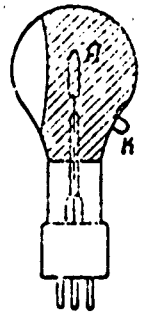

Fig. 5

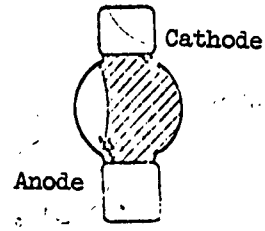

Fig. 6

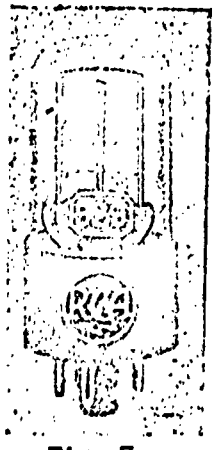

Fig. 7

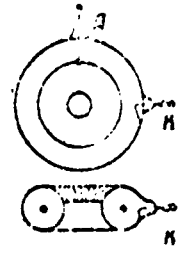

Fig. 8

shown in Fig. 7. In this case the antimony-cesium cathode is produced on a plate while the anode and cathode leads are attached to the pins of the base.

Among the designs with a central anode are ring-type phototubes intended for special operation in phototelegraphic broadcasting devices. Fig. 8 shows a diagramatically representation of this type of design; the annular shape proves extremely useful for intercepting diffuse-scattered light from the illuminated area of a scattering surface in the middle of the ring. Unfortunately, it is rather difficult to manufacture these phototubes both as regards glass blowing as well as in other respects.

Phototubes with a central cathode are only used in the laboratory and are rather difficult to make; the cathode is small in size and surrounded completely by the anode made in the form of a grid or metal coating on the walls of the tube. One such design is the spherical condenser used to measure the work function of the surface by the retarding potential method. The saturation current in this design is obtained for a true field equal to zero between the cathode and the anode (taking into account the contact potential difference).

Phototubes with plane-parallel electrodes always have a homogeneous electric field; these include the well-known electronic-optical image converters invented in 1934 by Kholst and others[7]. In these instruments, which consist of two beakers with plane parallel bottoms inserted one in the other, the bottom of the outside beaker is coated with a semi-transparent oxygen-cesium cathode.

A fluorescent screen coated on the bottom of the inside of the beaker is used as the anode.

The simple types of phototubes just described are obviously by no means all the designs used in practical work, for we have only pointed out the characteristic ones. A large number of different designs are considered in the well-known

books by Simon and Zurman /1/, Zvorykin and Wilson /2/, and also in the Shipalov and Nalimov reference book /3/.

The photo-electric devices used in television are considerably more complex both from the point of view of technology and design. In some of then the photocathodes are coated on thin wires (Braude system telecamera) and in others the photocathode has a mosaic structure and seems to consist of an enormous number of miniature phototubes with insulating gaps in between (Zvorykin iconoscope). In these cases the manufacture of the instruments is made even more difficult because of the fact that apart from photocathodes they usually contain incandescent cathodes, as well as a large number of other electrodes intended to control the electronic fluxes inside the device. However, a description of these instruments is beyond the scope of this article.

Table 1.

Type	Height in mm	Maximum diameter in mm	Weight in grams
Ts-1	110±5	55±1	50
Ts-3	57±3	26±1	15
Ts-4	107±3	39±1	55
STsV-51	59±3	29±1	15

At the end of this section we will give a table which compares the dimensions and weight of phototubes manufactured by the Elektrozavod. Those abbreviated to TsG are cesium gas-filled types and have an oxygen-cesium cathode; to increase their sensitivity they are filled with argon. Phototubes marked STsV are antimony-cesium vacuum types, manufactured for the time being in batches only. The main purpose of large phototubes (TsG-1 and TsG-4) is stationary cimena projection apparatus; small-size phototubes are used for portable film projectors, and obviously they can all be used in a number of other branches of engineering as well.

4. Luminous Characteristics

a) Spectral characteristics and integral sensitivity

The concept of the spectral and integral sensitivity of a phototube with a particular cathode is used to describe its photo-electric properties. The spectral sensitivity $i(\lambda)$ determines the photocurrent created when a luminous energy flux of 1 watt and a wavelength λ strikes the surface under consideration. We measure the spectral sensitivity in amperes per watt of the incident monochromatic radiation, or else (and the quantity has a more direct physical sense) in electrons per quantum of the incident radiation[8]. The magnitude of the quantum sensitivity in the case of a vacuum phototube cannot be greater than a half[9]; it shows directly which portion of the incident monochromatic radiation is being usefully employed in the given cathode. If the spectral sensitivity of the given cathode is known, the regions of the spectrum recordable by the given cathode to the greatest extent are also determined; if the spectral sensitivity is given, the photocurrent created in the phototube circuit when illuminated by any light source with a given energy distribution for the spectrum can also be calculated.

Experimental determination of spectral sensitivity, particularly in absolute units, involves a number of difficulties,, however, and requires the use of monochromators, measurement of the energy distribution through the spectrum with sensitivity thermocolumns and mirror galvanometers, or electrometers to record the weak photocurrents produced. However, in the most important cases in which phototubes are used in engineering, they do not operate under conditions of monochromatic illumination, but white light illumination from natural or artificial sources. Hence, for practical purposes it is often only necessary to know the overall photocurrent created in the phototube circuit when a beam of white light of given intensity strikes it. The luminous flux incident on the phototube can be measured more conveniently in light units (lumens) rather than energy units (watts). Thus, to assess

the sensitivity of a phototube working in the visible region of the spectrum, it is advisable to introduce the concept of integral sensitivity K which is determined by the saturation photocurrent created in the phototube circuit when a unit of luminous flux from a definite source impinges upon it. This reservation with respect to the selection of a light source is very important since the nominally identical luminous fluxes, having been obtained from sources of different spectral energy distribution, create different currents when incident upon the same phototube. At the present time a hundred-watt gas-filled incandescent bulb with a tungsten filament, the color temperature of which is 2848° K (true temperature of surface 2800° K) is used as a temporary standard for this source[10].

The relationship between the integral and spectral sensitivity of a given photocathode, on the basis of the above-given definition of the integral sensitivity, can be expressed by the equation

$$K = \frac{\int_0^{\infty} i(\lambda) E(\lambda, T) d\lambda}{N \int_{\lambda_1}^{\lambda_2} v(\lambda) E(\lambda, T)\, d\lambda} \cdot \frac{A}{lm}. \qquad (1)$$

Here $i(\lambda)$ is the spectral sensitivity of the photocathode in terms of amperes per watt of the incident energy with wavelength λ, $v(\lambda)$ is the coefficient of relative visibility with wavelength λ, N is the maximum coefficient of visibility of the radiation (621 lm/w) and $E(\lambda, T)$ is the spectral density of the incident radiation. This quantity can be given in relative units since it is also part of both the numerator and denominator in the given equation. By virtue of the difference in functions $i(\lambda)$ and $v(\lambda)$, variation in the temperature of the illuminator may substantially alter K by means of the function $E(\lambda, T)$. In view of the importance of this problem, we will deal with it in greater detail and consider two typical cases.

As we shall see later, the spectral sensitivity of the oxygen-cesium cathode is high in the red and infra red regions of the spectrum. Let us assume that the

oxygen-cesium phototube is illuminated by a nominally unchanged luminous flux, for example, one lumen, but that the temperature of the illuminator may gradually rise[11]. Here, in accordance with Wien's law, the spectral density $\underline{E}(\lambda, \underline{T})$ in terms of relative units (percent of the maximum density) in the region of small λ increases in the blue region of the spectrum, and falls correspondingly in the red region. As a result of the redistribution of energy from the red region, where the values of $\underline{i}(\lambda)$ for the phototube in question are high, to the blue region where $\underline{i}(\lambda)$ is smaller, the numerator in Eq. (1) gradually decreases, which in turn reduces the integral sensitivity $\underline{K}$, since the denominator in the equation according to our premise, is invariable. Thus, the integral sensitivity of oxygen-cesium phototubes should decrease as the temperature of the illuminator is increased[12]. Conversely, in the case of antimony-cesium phototubes, the spectral sensitivity of which is high in the blue region of the spectrum, an increase in the temperature of the illuminator should be accompanied by an increase in the integral sensitivity.

If the spectral characteristics of phototubes are measured with fair accuracy, and differ comparatively little from one model of the particular phototube to another, the described variation in $\underline{K}$ may be calculated beforehand by numerical integration of the terms in Eq. (1) for different illuminator temperatures. Fig. 9 shows graphs obtained by the investigator on a theoretical basis, and then verified experimentally, illustrating the variation in K for oxygen- and antimony-cesium phototubes (curves a and b). The temperature range selected covers the region most important in practice as the filament lamp illuminator; the integral sensitivity of both types of phototubes is taken as 100% at a true illuminator temperature of 2300°K.

In a number of cases, first and foremost, in television broadcasts under conditions of natural illumination, it is important to know the sensitivity of the phototubes for daylight ($T_{col} \sim 5000 - 6000$°K). Here the difference in sensitivity

between the phototubes of the two types becomes still more marked - K for antimony-cesium phototubes increases b a factor of about 3.5, compared with its sensitivity at $T_{\text{true}} = 2300°K$, attaining $160^{\mu A}/lm$ for the best specimens, and up to 10 - $12^{\mu}A/lm$ for the oxygen-cesium type. The sensitivity of antimony-cesium phototubes treated with oxygen may attain $250^{\mu A}/lm$ in these circumstances.

Let us now look at the spectral characteristics of different phototubes.

Fig. 10 shows the characteristics calculated per unit of incident energy for oxygen-cesium cathode phototubes; the y-axis at the peak points is taken as 100%. Curve a relates to the normal cathode while curves b and c relate to the cathode with a surface further coated with silver by vaporization so as to improve the sensitivity. Curve b is taken from the work by Khlebnikov and Sinitsyn /42/, curve c from Asao /41/. Curve a has a characteristic maximum lying close to the infra red region (about 8000 Å); the shape of the curve is usually much the same for different investigators for both versions of the manufacturing process (cathode on the inside of the glass and cathode on the plate). Slight technological differences in the manufacture of cathodes are comparatively unimportant (the thickness of the oxide layer and the activation temperature should not, however, differ too much from the values given in Section 2). Curves b and c, on the other hand, differ greatly from each other, as we can see, although they relate nominally to the same cathode. Indeed, by altering the technological process - the amount of vaporized silver, duration of heating, thickness of initial photo-active layer on the cathode, we can vary the position of the wavelength peak on the curve (from 6000 to 8500 Å) and the red limit on a wide scale. Thus, if there is a typical spectral characteristic (curve a) for a cathode obtained by normal technological procedure, for cathodes with additional silver, we can only show that their spectral curves are usually marked by higher values $i(\lambda)$ in the visible region of the spectrum. Detailed examination of

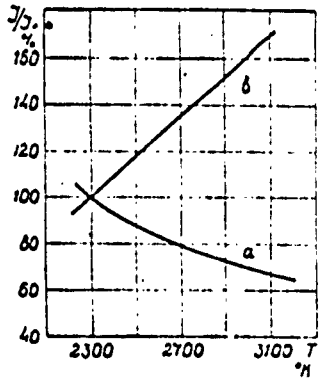

Fig. 9

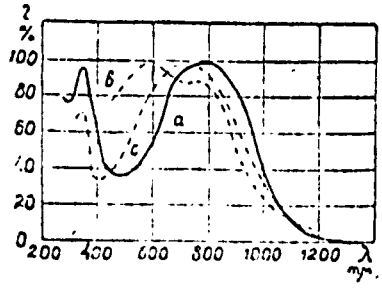

Fig. 10

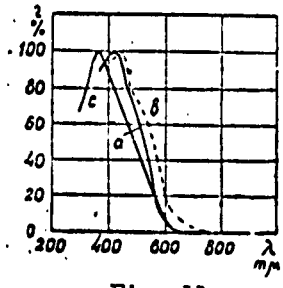

Fig. 11

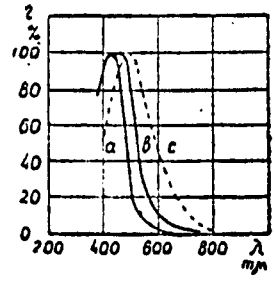

Fig. 12

spectral characteristics for these cathodes is contained in original articles /31, 32, 34, 41/ and also in De Bour's book "Electronic emission and adsorption effects".

The spectral characteristics for antimony-cesium phototubes are shown in Fig. 11. Curve a relates to the ordinary antimony-cesium cathode /51/, and curve b to an oxygen-sensitized cathode /25/. Just as in the previous graph, the y-axes are taken as 100% at the maximum. Oxygen treatment of the cathode results in a shift in the whole curve towards higher wavelengths. The absolute spectral sensitivity close to the maximum increases only slightly in this case. Curve c relates to RCA phototubes /28/, one of which is shown in Fig. 7. On all the curves the decline in the ultraviolet region of the spectrum is due to the absorption of light by the glass bulb.

Lack of sensitivity to infra red rays prevents us using antimony-cesium cathode phototubes for signal and communication systems with invisible rays, but makes them much more suitable at the same time for phototelegraphy, where they provide an incomparably better light transmission than the oxygen-cesium phototubes that used to be used /49/. Another specific use of antimony-cesium phototubes, also related to the shape of their spectral characteristics, is their measurement of the intensity of x-rays. The maximum radiation from calcium tungstenate ($CaWO_4$) fluorescing when acted on by x-rays lies exactly in the region of the spectrum in which the sensitivity of the cathode is extremely high, hence the combination of a $CaWO_4$ screen and an antimony-cesium cathode may act as a very sensitive x-ray indicator.

Fig. 12 shows several spectral characteristics of phototubes with cathodes that are used at the present time in laboratories rather than on a wide scale. The curves are shown as before in relative units. Curve a relates to a sulphur-potassium cathode /3/, curve b to a sulphur-cesium cathode, and c to a bismuth-cesium cathode

sensitized with oxygen. The sulphur-potassium cathode obtained by treating the surface of pure metal potassium in sulphur vapor was the first cathode to be commonly used in engineering phototubes. The sensitivity of these phototubes is high in the blue-violet region of the spectrum where there is a clearly marked selectivity maximum; the red limit lies at about 7000 Å. A similar spectral sensitivity curve is shown by hydrogen-potassium phototubes. The low and instable integral sensitivity of sulphur-potassium and hydrogen-potassium phototubes is their main defect. Sulphur-cesium phototubes, which are analogues of the oxygen-cesium type, were only developed comparatively recently /66/. In integral sensitivity they are inferior to oxygen-cesium ones, but are superior to them in the blue-green region of the spectrum (the maximum lies at about 4800 Å. The bismuth-cesium cathode /45, 54/ is an analogue of the antimony-cesium one, but is not so sensitive; just as in the case of the antimony-cesium cathode, oxygen treatment may improve the sensitivity of it.

Table 2 contains a brief summary of the results of spectral investigations of different cathodes and measurements of their integral and quantum sensitivity. The first column shows the type of cathode, the second shows the structure of the cathode in terms of the symbols suggested by De Bour. Here the first chemical symbol in brackets shows the material of which the backing is made; after the dash we have the components making up the intermediate semiconducting layer; finally, after the second dash we have the type of atom adsorbed on the surface. The third column shows the normal red limit for the photocathode of the given type, while the fourth column indicates the position of the maximum on the spectral sensitivity curve. If the given cathode has several maxima (oxygen-cesium, rubidium and potassium cathodes) the position of the long-wave maximum is indicated. The fifth column gives the integral sensitivity in terms of micro-amperes per lumen for the true temperature of the illuminator - 2800°K. Finally, the last column shows the quantum sensitivity of the cathode in terms of electrons per quantum of the incident radiation at the peak point on the spectral sensitivity curve. The figures contained in the table

Table 2

Type of photocathode	Structure of cathode (according to De Bour)	λ_o Å	λ_{max} Å	K μA/lm	$K\lambda_{max}$ election/quantum
1. Hydrogen-potassium . . .	[K] - KH - K	6800	4300	1-2	-
2. Sulphur-potassium . . .	[K] - K_2S - K	6800	4300	2-3	0.025
3. Oxygen-potassium . . .	[Ag] -K_2O.Ag.K-K	8000	4600-5200	10-20	-
4. Oxygen-rubidium	[Ag] -Rb_2O.Ag.Rb-Rb	10000	5600-6800	15-20	-
5. Oxygen-cesium	[Ag] -Cs_2O.Ag.CsCs	12000	7400-8000	20-40	0.003
6. Oxygen-cesium with additional silver . .	[Ag] -Cs_2O.Ag.Cs.Ag-Cs	to 16000	6000-8500	to 75	-
7. Sulphur-cesium	[Ag] -Cs_2S.Ag-Cs	7000	4800	10-20	-
8. Selenium-cesium	[Ag] -CsSe.Ag-Cs	7000	4800	10-20	-
9. Antimony-cesium	$\frac{Ni}{glass}$ -$SbCs_3$.Cs-Cs	7000	4200	50-60	0.25
10. Antimony-cesium sensitized with oxygen	- ? -	9000	4300	80-140	0.25-0.30
11. Bismuth-cesium	$\frac{Ni}{glass}$ -$BiCs_2$.Cs-Cs	7500	4500	20-25	-
12. Bismuth-cesium sensitized with oxygen . .	- ? -	9000	4600-6000	30-40	-

should obviously not be regarded as exact; particularly extensive variation from specimen to specimen, even when the technological procedure is unchanged, may be found in the figures for integral and quantum sensitivity.

We can see from this table that the high integral sensitivity of oxygen-cesium cathodes is not due to their high quantum sensitivity, but to the extremely low work function, and as a consequence, the widely stretched out nature of the spectral curve - over the whole of the visible and close to the infra red region. The spectral sensitivity of antimony-cesium phototubes, conversely, is concentrated in a comparatively narrow region of the spectrum, although their quantum sensitivity, as was first pointed out by the investigator, attains enormous values, at least five times greater than all values reliably observed up to the present time for the case of an external photo-effect. The tremendous quantum sensitivity of these phototubes combined with the comparatively high work function opens up tremendous prospects for using them to record low light intensities (photon counters, photo-electric registration of mitogenetic radiation converted into visible light by means of fluorescence, photo-electric recording of the passage of stars, and so on).

b) Relationship between photocurrent and luminous flux. Distribution of sensitivity over surface of photocathode

According to the first law of photo-electricity, the photocurrent should be strictly proportional to the radiant flux. Hence, when measuring the luminous flux incident on the phototube, the current in the latter's circuit should undergo proportional changes, provided the spectral composition of the luminous flux remains unchanged. In commercial phototubes this simple law ceases to be absolutely strict and in the region of high illumination deviations from direct proportionality are appreciable. These deviations may be due to different factors - charges on the glass walls of the tube, photo-electric fatigue, a spatial charge occurring when the

illumination is high, and so on. Particularly extensive deviation is observed in the case of antimony-cesium phototubes and the reason for it is considered in the next section. In the case of oxygen-cesium phototubes, we usually observe a reduction in sensitivity at high illuminations on account of the fatigue of the cathode during the actual measurement. It should be kept in mind, for practical purposes, that in the region of small luminous fluxes, no greater than several tenths of a lumen, when concentrated beams of light are not used and there is sufficient potential difference maintained between the cathode and anode for saturation, the proportionality between the photocurrent and the luminous flux is fully retained.

Fig. 13 shows the luminous characteristics[13] for antimony-cesium phototubes /44, 55/. As we can see, for luminous fluxed greater than 0.1 lm, the luminous characteristics ceases to be linear, and we observe both an increase and decrease in sensitivity. The reasons for these anomalies as has already been mentioned, will be considered later. For the moment we will only point out that all these effects are observed solely in the case of phototubes with cathodes on the inside of the glass, and not on a solid metal backing.

When elucidating the problem of proportionality between the photocurrent and the luminous flux, we must take into account the different sensitivities of the cathodes at different points, and therefore make all measurements with the same diaphragm and fixed position of the luminous spot on the cathode surface. The degree of non-homogeneity of the surface differs with different types of cathodes. It is particularly high in the case of hydrogen- and sulphur-potassium cathodes /3/; however even in the case of the oxygen-cesium cathode the oscillation in sensitivity may attain 50 - 100%, given a light probe dimension of about 1 mm^2. Antimony-cesium photocathodes are the most homogeneous, but even in their case, as shown by Vekshinskiy's detailed study of the problem /57/ with a light probe, the width of

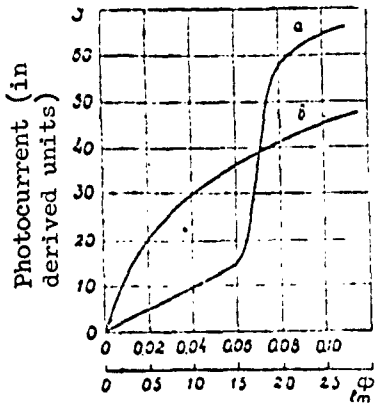

Fig. 13

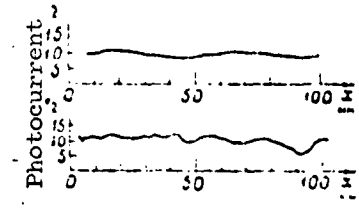

Fig. 14

which was only $8 \cdot 10^{-2}$ mm and length 0.86 mm, clearly-marked inhomogeneities were found, attaining tens of percent of the mean photosensitivity. Fig. 14 shows curves for the variation in sensitivity of different points along the antimony- and oxygen-cesium cathode[14], taken from Khlebnikov and Zaytsev /39/. The area of the luminous spot for these curves was 1.5 mm^2.

The different sensitivity of the photocathode at different points along it must be taken into account in all cases when transforming luminous impulses into electric ones, and the luminous flux is not modulated by varying the intensity of the light beam, but by varying its dimensions. We come across this type of modulation, for example, in sound motion pictures, when reproducing photograms recorded by the transversal method, in which the non-constant sensitivity of the photocathode on the surface may be a source of considerable distortion.

Footnotes

1. The guaranteed lifetime is 100 hours instead of 1000!

2. The exception is the Gekord portable apparatus which uses gas filled phototubes and does not change the overall picture.

3. A detailed description of the properties and methods of obtaining and cleaning the materials used in electric vacuum production and, in particular, the manufacture of phototubes is contained in the books 1) Espe and Knol' "Technology of Electrovacuum materials" and 2) Ivanov, "Technology of electrovacuum materials".

4. For description of these pumps see Hickman, Journ, Appl, Phys., 11, 303, 1940.

5. Here if copper oxide is used the reaction is strip; from the point of view of energy this reaction is less advantageous than reducing silver oxide, on account of which activation of the cathode takes place at a faster rate than absorption of the cesium by the getter. For further details see Luk'yanov /17/.

6. For a detailed description of the silver plating glass for photocathodes see article by Gol'dreykh /40/.

7. See, for example, UFN 17 (4), 1937.

8. We should recall that for a transition from spectral sensitivity at the given wavelength λ in terms of amperes per watt to sensitivity in terms of electrons per quantum, we must use the equality:

$$1\ \frac{amp}{watt} = 1.24 \cdot 10^{-4} \lambda^{-1}\ \frac{electrons}{quantum}$$

9. Since half the photo-electrons created, by virtue of symmetry, have a pulse directed inside the cathode, and half have a pulse directed towards the outside surface.

10. See resolution of Kiev Electronics Conference, 1940, Phiz. zap., vol. 9, Issue 2, 1940.

11. From now on we will restrict ourselves to the illuminator temperature

range usually encountered when using artificial or natural light sources - from 1000 to 6000° C.

12. We are considering the whole time oxygen-cesium cathodes of the normal type, without the extra coating of silver; the spectral characteristics of cathodes of this type may differ substantially among themselves, see below.

13. The top scale relates to curve a and the bottom to curve b.

VACUUM PHOTOTUBES

S. Yu. Luk'yanov

5. ELECTRICAL CHARACTERISTICS

a) Volt-Ampere Characteristics

We shall now examine the volt-ampere characteristics of phototubes of different types of construction, especially the volt-ampere characteristics of antimony-cesium phototubes, which show a number of anomalies.

The volt-ampere characteristics for vacuum phototubes with any type of cathode, at any light intensity and with any construction of the photocell give the saturation current, provided the anode voltage is sufficiently high (we shall leave antimony-cesium phototubes out of consideration for the moment). The saturation potential depends, of course, on the construction of the phototube.

For phototubes with a central cathode the saturation potential is very low — the saturation current is obtained at an actual field between the anode and cathode which is equal to zero. In this case all the photoelectrons, regardless of their initial energy and direction, are intercepted by the large surface of the anode, which surrounds the small central cathode. None of the photoelectrons, regardless of direction or original velocity, has a chance to return to the cathode if the accelerating field is directed from the cathode to the anode.

The situation is different with phototubes with central anode which are ordinarily used in industry. In this case the saturation current is reached only with an anode potential of the order of 50-100 v. This occurs because electrons from the surface of the cathode fly off in all possible directions and often, in the case of weak fields, not being sufficiently deflected to reach the anode, escape it and return to other parts of the cathode, which has larger dimensions, without having contributed to the measured photocurrent. The saturation potential in these phototubes must therefore increase with an increase in initial energy of the photoelectrons, i.e. with a decrease in wavelength of the light causing the photoeffect. This is illustrated by the volt-ampere characteristics obtained by Ives (Fig. 15) by illuminating a spherical phototube with a small central anode (also spherical) by beams of different wavelength. As can be seen, a decrease in wavelength actually results in a noticeable increase in the saturation potential ($\lambda_2<\lambda_1$).

Let us now return to a consideration of the volt-ampere characteristics of antimony-cesium phototubes. Just as in the case of the light-transfer characteristics, all the anomalies are observed only in the case of phototubes with the cathode applied to glass; in the case of a metal sublayer, however, the volt-ampere characteristics have the usual form with clearly defined saturation. It should also be noted that the average volt-ampere (and also the light-transfer) characteristics

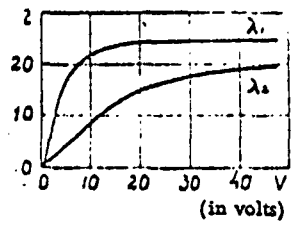

Fig. 15

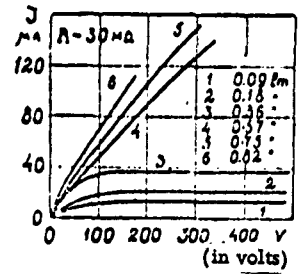

Fig. 16

obtained with a given phototube for low values of incident light flux often change upon transition to higher values of light flux. As an illustration of this, Figure 16 shows a family of volt-ampere characteristics [56] for a phototube with the cathode on glass, the resistance of whose layer, measured between the sealed lead-ins, amounted to about 30 megohms. It can be seen that as the light flux increases, the saturation region on the curves disappears and the photocurrent increases monotonically with increasing anode voltage. Sensitivity of the phototube at high values of voltage and light flux naturally reaches very high values (300-400 μa/lm).

The following explanation may be given for this phenomenon: due to the large longitudinal resistance of antimony-cesium cathodes on glass, the potential of points sufficiently distant from the platinum lead-in may differ greatly from the potential of the lead-in when the phototube is illuminated (i.e. in the presence of a photocurrent). In consequence of this, part of the emitted electrons may fall, not on the anode, but on portions of the sensitive layer with elevated potential and there cause secondary electron emission, which will result in an increase in the measured current. Thus, the anomalous volt-ampere characteristics are explained, from this point of view, by the imposition on the true photocurrent of a secondary emission current. The existence of a difference in potentials between the lead-in and different points on the illuminated photocathode was substantiated by the direct measurements of Lukirskiy and Lushevaya [44], to whom the explanation just given is also due, as well as the first study of the properties of antimony-cesium photocells in the USSR.

On the basis of the concepts that have been developed, the appearance of anomalies at high values of incident light flux becomes understandable — the higher the value of light flux, the greater the voltage drop at the layer, the sooner secondary emission processes begin to play a role and the sooner it becomes possible for current amplification to occur within the device. At low values of incident light flux, due to the smallness of the current flowing along the cathode, the voltage drop along the layer remains small right up to the onset of saturation and current amplification does not occur.

Furthermore, it is understandable that in the case of cathodes with very thick layers, the longitudinal resistance of which is small, anomalous phenomena may not be observed at room temperature, but they must be observed (and this actually takes place) on cooling the cathode to the temperature of liquid air, when its resistance increases sharply. For the same reason, on cathodes with very thin layers and with high longitudinal resistance, these phenomena are very marked, while on cathodes applied to a thick metal sublayer, where the influence of longitudinal resistance is

excluded, they are completely absent.

In similar manner it is easy to explain the anomalous light characteristics which we discussed above. Let us look, for example, at curve a in Figure 13, plotted for V_a=250 v. It is evident that beginning at 0.06-0.07 lm, the linear relation between current and light flux disappears and the photocurrent rapidly increases. From this moment, the voltage drop due to the current flowing along the layer becomes sufficient for the appearance of secondary emission, which also leads to a rapid increase of current in the anode circuit. If, however, a lower value of anode potential were used (for example, 100 v), the curve would have a different character. As a matter of fact, under these conditions the potential difference ΔV at the layer will still be insufficient for intensive secondary emission (it is obvious that ΔV is always less than V_a), but, at the same time, some portions of the cathode will be in a very weak electrical field and the electrons emitted therefrom will not be collected at the anode. This case is shown in curve b of the same figure. It is easy to understand that at different values of anode voltage, different phototube constructions, longitudinal resistances and cathode temperatures, it is possible to obtain quite varied light-transfer and volt-ampere characteristics by which it is possible to explain the apparent contradiction in the results of different observations and the lack of coordination in the explanations of the described anomalies which have been present in the literature for some time (on this subject see [53, 59]).

b) Fatigue and Length of Service. Influence of Temperature; Dark Current.

The problem of constancy of sensitivity of oxygen-cesium phototubes with time has been the subject of numerous investigations [34, 37]. The basic result thus obtained may be formulated as follows: the sensitivity of oxygen-cesium cathodes at high illumination intensities shows a fairly rapid fall within a short period of time (10-20 hours) with subsequent stabilization at a level of 20-25% of the initial value. The rate of decrease and the final values of sensitivity depend on many factors — cathode illumination, spectral composition of the incident light, applied voltage, and temperature.

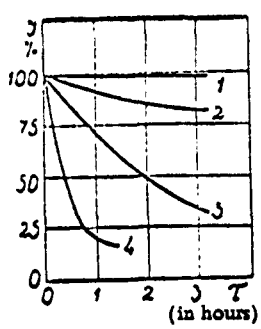

Fig. 17

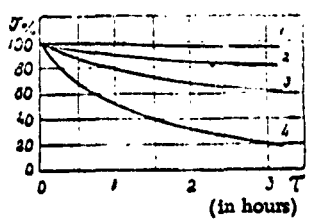

Fig. 18

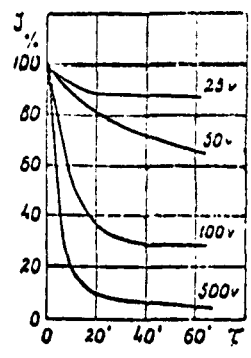

Fig. 19

The role of these factors is illustrated by the curves shown in Figures 17, 18 and 19. Figure 17, taken from the work of De Boer and Teves [34], shows the change in sensitivity when the cathode is illuminated with light of different colors; curve 1

was obtained by illuminating the cathode with infrared light, curve 2 with red light, curve 3 with green and 4 with violet. The curves show that fatigue is great when the cathode is illuminated by light of shorter wavelengths and is practically absent when infrared is used for illumination. In this connection, as shown by spectral studies, cathode fatigue is accompanied by an increase in work function and a decrease in intensity of the long-wave maximum. With increasing illumination the cathode becomes fatigued more quickly; this is shown by the curves of Figure 18 which were taken, as were those of Figure 19, from the study by Timofeyev and Kondorskaya [37]. Curve 1 was obtained with an illumination of 50 lx, curve 2 — 250 lx, 3 — 500 lx and curve 4 — 1000 lx. Finally, the influence of the longitudinal voltage is clearly illustrated by the curves of Figure 19; these curves were taken while the cathode was simultaneously cooled to the temperature of liquid air, which resulted in a considerable increase in cathode fatigue.

A fatigued photocathode regains its original sensitivity completely or partially when kept in the dark for some time, and more rapidly if it is heated or illuminated by infrared light. The reasons for fatigue have been examined by many authors, and especially by De Boer, but up to the present the problem has not been definitely explained.

A typical curve showing the change in sensitivity of a standard gas-filled phototube made by Elektrozavod (TsG-4) after prolonged operation is shown in Figure 20 (Curve 1). The curve was plotted at an anode voltage of 240 v, which corresponds to the normal operating voltage of this phototube with continuous illumination of the cathode by white light; the light flux incident at the cathode was ~ 0.02 lm.

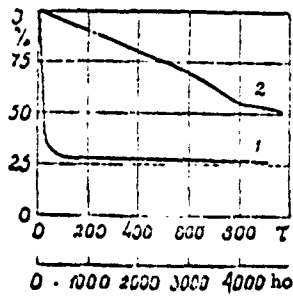

Fig. 20

It should be noted that the constancy, with time, of the characteristics of cesium oxide-silver phototubes, is considerably higher than that of ordinary cesium oxide phototubes. Thus, according to recent measurements by Khlebnikov and Sinitsyn [42], after 350 hours of continuous operation with an illumination of 20 lx, these phototubes retained about 80-90% of their initial sensitivity.

The constancy of sensitivity of vacuum phototubes with antimony-cesium cathode under the conditions characteristic of sound-film operation was recently studied in detail by Khlebnikov and Sinitsyin [60]. It appeared that the fatigue of these phototubes was considerably less than that of cesium oxide phototubes. Thus, after 5000 hours of continuous operation with an illumination of about 20 lx, these phototubes, regardless of construction and initial sensitivity, decreased by only 30-40% in sensitivity. Curve 2 of Figure 20 shows how the sensitivity of a standard phototube made by Elektrozavod changes with continuous operation; this curve, too, was plotted at the low incident light flux of ~ 0.02 lm. The scale of the abscissa for the two types of phototubes is different: the larger scale refers to curve 1; the smaller (lower) scale refers to curve 2.

The temperature stability of cesium oxide phototubes is considerably lower than that of antimony-cesium phototubes. Thus, in a number of cases, on raising the temperature to 100°C a decrease in sensitivity was noted which amounted to 50% of

the initial value; a noticeable change in sensitivity was observed even at 60°C. An especially troublesome factor is the absence of any regularity in the changes that occur even if we restrict ourselves to a small temperature interval (below 50°C; for details see [38]). At higher temperatures, as a rule, a decrease in sensitivity is observed, but the magnitude of this decline varies from sample to sample. For example, Figure 21 shows the change in sensitivity with temperature of two sample phototubes made by Elektrozavod [38]. Decreasing the temperature to -50°C causes a decrease in sensitivity of the phototubes, but after remaining for a long time at room temperature (17 hours at 20°C) the initial sensitivity is recovered.

An increase in temperature to 50°C has practically no effect on the sensitivity of antimony-cesium phototubes. Thus, factory production is guaranteed to maintain constant sensitivity within the limits of 90 to 105% of the initial value within the temperature range of 20 to 50°C. Lowering the temperature also has little effect on sensitivity, provided influence of the resistance of the cathode (the metal sublayer) is excluded. Otherwise, a sharp decrease in sensitivity caused by an increase in the longitudinal resistance of the cathode is observed, with the result that parts of the cathode remote from the platinum lead lie within the greatly weakened electrical field of the anode.

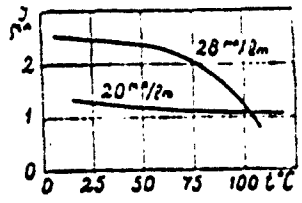

Fig. 21

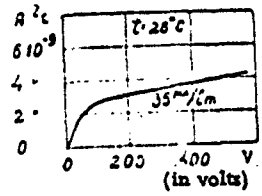

Fig. 22

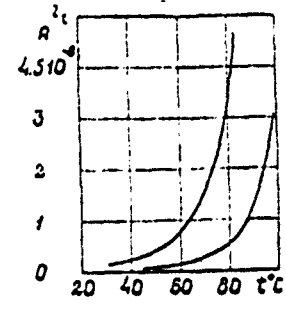

Fig. 23

When the temperature of phototubes is increased, along with the change in sensitivity, one other undesirable phenomenon is observed — the occurrence of significant dark currents. Dark currents are caused by thermionic emission of the cathode and by conduction currents on the glass. The dependence of dark currents on the applied voltage difference and the order of magnitude of the currents observed at room temperature for oxygen-cesium phototubes is illustrated by the curve shown in Figure 22 [38]. The rapid increase in dark current with increasing temperature is illustrated by the curves of Figure 23 [38], which were plotted for two sample oxygen-cesium photutubes made by Elektrozavod. Thermionic emission of the cathode comprises most of the observed dark currents at high temperature, which may easily be verified by measuring the dark currents with the electrodes connected in reverse.

The large value of the work function of antimony-cesium cathodes would lead one to expect, in this case, the appearance of dark currents of considerably smaller magnitude. As a matter of fact, the thermionic emission in these phototubes, as we

have already mentioned, is approximately two orders of magnitude less than in the case of cesium oxide phototubes, which results in small dark currents even at relatively high temperatures. The dark currents caused by the conductivity of glass may be greatly reduced by suitable construction of the phototube.

In concluding this review of the electrical characteristics of vacuum phototubes it should also be mentioned that photoelectron emission takes place non-inertially since with the incidence of a time-varying light flux at a phototube the photo current reproduces the magnitude and shape of the light signals falling on it without distortion or retardation. The shunting effect of the interelectrode capacitance is significant only in the region of radio frequencies.

6. PHOTOTUBE APPLICATIONS. REFERENCE DATA

a) Photutube Operating Conditions in Various Fields of Technology; Selection of Phototubes.

In examining the various fields of application of phototubes we encounter a great variety of conditions under which they are used. Consequently, we also encounter a great variety of requirements which must be met in choosing the type of phototube in order that it be most suitable for a given use. We shall briefly summarize the operating conditions for phototubes in some of the most interesting and important fields of technology and indicate to what degree the existing phototubes permit solution of new technical problems.

1) Sound Films

Basic factors which determine the selection of the type of photoelectric apparatus for use under given conditions are: 1) the amount of light flux incident at the phototube; 2) the spectral composition of the light; 3) the frequency of the light pulses.

According to data of the Lenkinap plant and measurements by the author, the maximum values of incident light flux Φ_0 that can be accomodated by the phototube types used in our sound film equipment are:

1) Stationary (sound unit KB) $\Phi_0 = 0.012$ lm
2) Portable ZP-16 $\Phi_0 = 0.004$ lm
3) Portable Gekord (K - 25) $\Phi_0 = 0.0016$ lm

The light source in all cases is an incandescent lamp which gives white light, but the temperature of the lamp filament varies. In the first two cases its true temperature is close to 3000°K, while in the latter it amounts to only 1800°K. As regards the band of frequencies utilized, practice has shown that in order to obtain completely satisfactory fidelity from the reproduced recording it is sufficient to use a frequency band between 50 and 8000 cps.

The numerical data presented here permit the following direct conclusions:

1) Regardless of the type of phototube actually chosen as most satisfactory for sound reproduction, the light fluxes at our disposal are so small that great amplifica-

tion of the original photocurrents is required. As a matter of fact, in the presentday amplifiers used with sound films — for example type US-8 — power amplification amounts to about 5×10^{10} or 107 db.

2) The high filament temperatures of the lamps in the first two types of equipment is an additional argument in favor of the use of antimony-cesium rather than oxygen-cesium phototubes under these conditions (see curves, Fig. 9). On the other hand, with the portable Gekord the use of antimony-cesium phototubes is not recommended since under these conditions their integral sensitivity falls to approximately 40 μa/lm, becoming practically identical with the sensitivity of cesium-oxide vacuum phototubes and is far below the sensitivity of gas-filled types.

3) The range of frequencies used permits the use of gas-filled phototubes.

The conclusions drawn may be made more precise by determining the effective values of the voltage impulses ΔV_{eff} occurring at input resistor R_g of the amplifier (the value of R_g is limited by the shunting action of the parasitic capacitance of the phototube and the lead-in wires. If we designate the modulation coefficient of the light flux by μ and the phototube sensitivity by K, then

$$\Delta V_{eff} = \frac{1}{\sqrt{2}} \mu K \Phi_0 R_g.$$

Calculation shows that when oxygen-sensitized antimony-cesium vacuum phototubes are used and the value of R_g correctly chosen, the following results are obtained:

Stationary equipment	$\Delta V_{eff} = 25$ m V
ZP - 16	$\Delta V_{eff} = 8.5$ m V.

These values of ΔV_{eff}, of course, are entirely sufficient for subsequent amplification and assure the dynamic range essential for high-quality reproduction. Amplification of the original signal by the use of gas-filled phototubes is not necessary and, under the given conditions, does not in any way compensate for the defects that arise (lag in response, decrease in stability with time, increase in noise level).

Thus, in these types of apparatus the use of antimony-cesium vacuum phototubes provides an excellent solution of the problem. For the portable Gekord apparatus with ordinary amplifying equipment the use of gas-filled phototubes is still essential.

At the present time, in addition to the described possibility of using a combination of phototube with an ordinary resistance-coupled amplifier, we may use equipment with photomultipliers (for example, the KEO-4 apparatus) and with thallium sulfide photocells[15] (requiring amplifiers with special transformer input). In all cases it is possible to attain a satisfactory solution of the problem. At the present time the first variant appears to be the most suitable because it assures a better quality of reproduction and greater dynamic range with existing equipment. In the future, taking into consideration progress in the manufacture of photomultipliers and thallium sulfide photocells and the accumulation of experience in the use of new

[15] See Kolomnets, Elektrichestvo (5), 18 (1940).

systems, the choice between the indicated possibilities may have to be considered anew, taking into consideration not only technical factors but also economic ones, which will appear more clearly as a result of the competition of all systems in actual operation.

2) Television

The magnitude, spectral composition and frequency of the light impulses with which we are concerned in television transmission, as in the case of sound films, are the basic factors determining the operating conditions of photoelectric devices under a given set of conditions. High quality television requires that the transmitted image be broken down into a sufficiently large number of elements (about 2.7×10^5 in the case of a 450-line scan and standard aspect ratio). The light flux issuing from these elements must subsequently be received by a photoelectric device, transmitted and reproduced. Simple calculation shows that with image illumination of 1000 lux, the maximum light flux which may be obtained from a single element has a total magnitude of the order of only 6×10^{-7} lm. The necessity of transmitting pictures of moving objects and, consequently, of transmitting a minimum of 25 frames per second, results in the fact that the frequency of the transmitted light impulses reaches 3×10^6 cps. As regards the spectral composition of the light, we ordinarily deal with dispersed light from natural or artificial sources which give a continuous spectrum. The magnitude of the light flux which we have indicated is so small and the frequency of the transmitted signals so large that the transmission noise level must be considerably higher than the signal itself. In order to reduce the signal-to-noise ratio (ψ) to a value that will guarantee reception of an image of good quality ($\psi \sim 50$), it is necessary either to sharply reduce the number of picture elements (by a factor of 100 !), which in turn would reduce the quality of the image, or else to greatly increase (also by a factor of a hundred) the illumination of the transmitted object, which, as a rule, is also unacceptable. An exception is the television transmission of motion pictures where the illumination limitations disappear and we obtain a sufficiently large value of ψ by using a vacuum phototube of good quality.

Thus, in using any amplifying equipment, high quality television transmission of ordinarily illuminated subjects with the aid of simple vacuum phototubes appears to be impossible. A solution has been found through the use of more complex photoelectric devices (iconoscopes) suggested by Zworykin in 1933 and based on the charge-storage principle. In the iconoscope the incident light flux from individual elements is used not only at the moment of transmission of the given element, but throughout the entire frame transmission period— the photocurrents that arise continuously charge the capacitors connected with individual elements of the photocathode (globules of the photocathode mosaic), whereas discharge of the capacitor occurs immediately at the time of transmission of a single element. The theoretical gain in sensitivity in changing from a simple photocell to an iconoscope should be equal to N, where N is the number of picture elements. This theoretical limit is far from being achieved in practice, but existing apparatus makes it possible to obtain transmission of good quality with relatively weak illumination. Up to the present, the iconoscope mosaic has been an array of miniature cesium oxide cathodes on silver globules. It is possible that in the future a high-grade antimony-cesium mosaic cathode will be obtained. In a similar manner, besides possessing greater sensitivity, the apparatus will give better color transmission of images. We have already called attention to this fact, which is associated with the shape of the spectral characteristic of antimony-cesium phototubes, and noted the applicability of the phototubes in phototelegraphy. We wish

to point out further that while the use of vacuum phototubes is essential in television because of the use of high frequencies, in phototelegraphy, in principle, one may also use gas-filled phototubes, which, however, ceased to be modern from the moment that antimony-cesium phototubes appeared.

3. The Use of Phototubes for Control, Signaling, and Inspection; Use in Measurement.

The number of different problems that arise in industry may be solved by various photoelectric schemes is enormous. Thus, phototubes are used in mass production for counting standard parts moving on a conveyor, for checking the size and shape of objects, for sorting objects according to color, and for sorting lamps according to light intensity. Phototubes in combination with appropriate electromagnetic mechanisms can automatically control machine tools and presses, automatically signal the appearance of smoke, measure the density of natural or artificial fogs, etc.

In all the variety of problems that have been enumerated, which amount to only a small part of the total, it is possible to distinguish some general conditions which the photoelectric arrangements used in these cases satisfy: all of them embody relay action. As a rule a phototube is used only in order to obtain a certain signal, the magnitude of which may or may not be proportional to the incident light flux while its form may differ arbitrarily from the form of the light signal, since the obtained photocurrent pulse is then used only to start and stop the associated counting, inspection or control mechanism. The frequency of the impulses used in solving such problems is ordinarily not large; the magnitude of the light flux, however, may vary widely depending on the concrete conditions and, while fairly large when using directed light beams, it may sometimes fall to very low values if the phototube must operate with diffused light fluxes. Thus neither linearity of the light-transfer characteristics nor absence of lag in phototubes in the cases examined appear to be essential. What does appear to be essential is as high a sensitivity as possible and the greatest possible constancy of the parameters of the phototubes with time (since such set-ups are ordinarily intended for prolonged operation). If the light flux which may be used are not too small, it is quite expedient in start-stop operation to link the phototube with a thyratrom, which makes it possible to obtain tremendous amplification immediately. In the case of very low light flux, the use of a thyratron is not worthwhile due to the impossibility of using sufficiently large input resistances; in this case electrometer tubes should be used and it is essential to select phototubes with sufficiently low dark currents.

The fields of measurement in which phototubes have been used with success include: objective photometry and pyrometry; measurement of the transparency of liquids (which finds exceptionally wide application in the chemical industry where quantitative analyses are continually carried out and automatically recorded, thus permitting the continuous control of processes); the measurement of light flux diffused in gaseous, liquid and solid media; the measurement of areas (photoelectric integrators), etc.

In all these phototube applications the constancy of sensitivity with time plays an exceptional role. In photometry, moreover, it is desirable to use phototubes with spectral response as close as possible to that of the eye; for this reason in lux meters and exposure meters operating under high illumination one ordinarily uses selenium barrier-layer photocells which are extremely portable and do not require

Table 3

	Designation of Elektrozavod photocell	1 U_a V	2 $U_{br.}$ V	3 K_0 μA/lm	4 i_t A	5 g μA/lmV	6 K_{320}/K_{10^4} db	7 K_{min}/K_{max} %	8 K_0/K_t ($t = 50°C$ db	9 τ in hrs.	10 K_T/K_0 %
1	TsG-1	240	> 320	⩾ 100	$1 \cdot 10^{-7}$	5—6	5.7	10—20	- 5	100	35
2	TsG-3	240	> 300	⩾ 150	$1 \cdot 10^{-7}$	5—6	4.5	10—20	+9	30	25
3	TsG-4	240	> 310	⩾ 150	$1 \cdot 10^{-7}$	5—6	5.2	10—20		100	25
4	TsGN-4	90	> 140	> 100	$1 \cdot 10^{-8}$	6—7	5		—3, +9	100	50
5	STsG-4	90	> 140	> 150	$1 \cdot 10^{-8}$	4	1.3	80	— 1, +0.5	100	60
6	STsG-51	180	> 275	> 150	$1 \cdot 10^{-9}$	4	1.5	80		100	60
7	STsV-4	90—240	—	80	$1 \cdot 10^{-8}$	0	0	80	— 1, +0.5	1000	50
8	STsV-51	90—240	—	80	$1 \cdot 10^{-9}$	0	0	80		1000	50

a source of current. If the light flux to be measured is small, the use of barrier-layer photocells is inconvenient because of the necessity for an amplifier. When photocells are used in pyrometry, the magnitude of the light flux incident at photocathode may change by many times; therefore it is convenient in this case to connect the photocell with a vacuum-tube voltmeter which has a logarithmic scale.

b) Parameters of "Elektrozavod" Phototubes.

Table 3 gives a summary of the electrical parameters of various phototubes manufactured by Elektrozavod[16]. For the sake of completeness, the table also gives the parameters of gas-filled phototubes.

The abbreviations "TsG" and "STsV" were explained above; the abbreviation "STsG" means "antimony-cesium gas filled" and "TsGN" means "cesium-oxide gas-filled low-voltage." Data on the construction of these four classes of phototubes were given in Table 1; the STsV-4, STsG-4 and TsGN-4 coincide have the same construction as TsG-4; the STsG-51 has the same construction as STsV-51.

The first column of Table 3 shows the operating voltage; for vacuum devices it need only exceed the saturation potential; for gas-filled phototubes, however, it is chosen at a point on the volt-ampere characteristic at which there is a sufficient gas amplification factor and, in addition, it must be sufficiently far from the breakdown voltage (at which self-maintained discharge occurs), since otherwise the phototube would become unstable (increase in noise, lagging reponse, etc.). The second column shows the breakdown potential in the dark; with the incidence of light flux at the cathode this value decreases. The third column gives the values of the

[16] From report by Rabotnova at the 1940 Kiev Conference on Electronics (Fiz. zap., Vo. 9, No. 2).

integral sensitivity at room temperature at the beginning of operation of the phototube when illuminated by a light flux of a few hundredths of a lumen from a light source with a true temperature of 2800°K. The fourth column gives the value of dark current at operating voltage. The fifth column gives the slope of the volt-ampere characteristic at operating voltage; for vacuum phototubes this value, of course, is equal to zero, since they operate under saturation conditions[17]. The figures in the sixth column show the decrease in output of the phototube, expressed in decibels, on increasing the frequency of interruption of the light falling on the cathode from 3100 to 10,000 cps. This value characterizes the lag of the phototube; in the audio-frequency region it is equal to zero for vacuum phototubes since electron processes are practically lagless at these frequencies. In this frequency range interelectrode capacitance (with a value of the order of 10 $\mu\mu$fd) is negligible. In the case of experimentally observed gas-filled phototubes a decrease in output is related to inertial processes in the buildup and decay of ion avalanches formed during gas amplification. In turn, the inertia of these processes is ultimately related to the lower mobility of ions in comparison with electrons, to secondary processes at the cathode during gas amplification and to the formation, in some cases, of metastable atoms. The sensitivity of photocathodes, as we know, is not identical at different points on the surface; aside from microscopic irregularities, the sensitivity of commercial phototubes, as a rule, is considerably greater at the cathode center than at the edges. The figures in the seventh column show the value (in percent) to which the sensitivity decreases on moving from the center of the cathode to its periphery. The figures in the eighth column show the change in integral sensitivity in decibels on increasing the temperature from room temperature to +50°C. The last two columns give the average time τ of relative stabilization of phototube sensitivity and the value of its residual sensitivity (in percent of initial) after the passage of time τ.

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The list of literature given below is, of course, not exhaustive. The older original articles on photocells have been omitted. Problems on the use of phototubes are considered in the majority of the books and review articles listed. Especially rich practical material, and also numerous references to original papers on various concrete problems in the use of phototubes in technology may be found in the works of Simon and Zurman [1], Zworykin Wilson [2] and Henney [15]. Popular literature is designated by an asterisk.

1. Books

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[17] For gas-filled phototubes the value of g increases rapidly as it approaches the breakdown potential. This fact makes it impossible to use especially large values of gas amplification factor since at large values of g high stability of supply voltage is required; moreover nonlinear distortions on illuminating the phototube with a variable light flux begin to appear.

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