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NOTES ON THE DESIGN OF GLOW DISCHARGE VOLTAGE STABILIZERS FOR PHOTOMULTIPLIER TUBE POWER SUPPLIES

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A series of high stability neon glow discharge tubes (OG3/85A2) was used to stabilize 1685 volts for the dynode resistance divider of a photomultiplier tube to an accuracy of $\pm$ 0.2%. The limit of stability and the ageing phenomena for the tube operating at reduced currents are discussed but not understood.

1. Introduction

It is generally recognized that the gain stability of a photomultiplier tube may be sharply dependent upon the constancy of the voltage distributed to the various dynodes. Long term voltage stability, excellent reset characteristics, and an expected lifetime of many years are known features of several glow discharge tubes developed during the last 15 years which make them extremely attractive as high voltage-low current stabilizers. The purpose of this report is to review the published work on the new glow discharge tubes, to discuss their application to photomultiplier voltage stabilizers, and finally to describe our experience in the use of this type of voltage source.

2. Stability Measurements

The basic principles of voltage stabilizers in general have been excellently described in a book[1]) by F. A. Benson, University of Sheffield, England. Benson lists several hundred references which deal with voltage stabilization problems, circuitry in particular, and special applications. Chapter 3 discusses voltage stabilization by means of the glow discharge tube and is of interest in this discussion. Many tube types, including some made in the United States, England, and Holland, are compared. Data are given for initial drift, some long term drifts, voltage jumps, temperature coefficients, striking and operating voltages, and voltage-current characteristics. On the basis of the Benson data, the most interesting tube for further study is the special high stability neon tube type 85A1†, which was the direct result of the pioneering work of T. Jurriaanse[2]) *et al.* at the Philips Research Laboratory, Eindhoven, Netherlands, in 1946. Later (1952–53) a smaller, seven pin version of the 85A1, named the 85A2, was manufactured. It is claimed[3]) that after an initial 100 hour running time, the maximum variation of operating voltage over any 8 hour period will be better than 1 part in 10^4, providing an initial period of 3 minutes is allowed for warming up. The temperature coefficient is given as -4.0×10^{-3} volt/°C per tube, which is only slightly larger (percentage-wise) than the coefficient for a Weston standard cell. By comparison, it will be recalled that a properly aged and temperature controlled standard cell has a voltage stability of about 1 part in 10^5 over a period of years[4]).

† The OE3/85A1 and the OG3/85A2 are distributed by the Amperex Electronic Corporation, Hicksville, Long Island, New York.

[1]) F. A. Benson, Voltage Stabilizers (Electronic Engineering Publishing House, London, 1950).

[2]) T. Jurriaanse, A Voltage Stabilizing Tube for Very Constant Voltage, Philips Tech. Rev. 8 (1946) 272.

[3]) Mullard Technical Handbook, Vol. 1A, Sheet Issue 3, 754-1, on Voltage Reference Tube 85A2 (Mullard Limited, London).

[4]) G. P. Harnwell, Principles of Electricity and Magnetism, 2nd ed. (McGraw-Hill, New York, 1949) p. 140.

Long term (2 to 3 years) stability measurements on small samples of the 85A2 and the 5651 neon tubes have been performed by W. G. Hoyle[5]). W. H. Weber[6]) observed a number of types of glow tubes, including the 85A2 and the 5651, for several weeks. In order to stabilize the 1000 to 2000 volts for a photomultiplier tube, a number n of glow discharge tubes must be joined in series, and the average behavior of these tubes determined. One expects the systematic behavior of the voltage due to temperature and current changes to be the same as for an individual tube, but the relative variation of the voltage due to random fluctuations in the individual tubes will be reduced by $1/\sqrt{n}$. Therefore, we have taken the liberty of averaging Hoyle's data and have replotted these on a linear time scale in order to emphasize the smoothing of the data as well as to show the long term behavior (see fig. 1). After an initial running time of 2000 to 3000 hours, one is impressed by the remarkable stability exhibited by both tubes (85A2 and 5651) for the next $2\frac{1}{2}$ years. In detail, the 85A2 has somewhat less initial drift and appears to have a longer lifetime at a current of 8 mA (as indicated by the rate of voltage rise at the end of 3 years) than the 5651 at 3.5 mA. Weber's measurements of the 85A2 also indicate an initial upward drift for the first two weeks of about the same magnitude, and the data seem to support the manufacturer's stability figures as indicated above. The behavior of the 5651 appears to be more variable in manufacture or operation than that of the 85A2. Weber finds from a sample of eight 5651's and four 5651WA's that the voltage increase with time is similar to the 85A2, whereas Hoyle's data indicate that the voltage decreases.

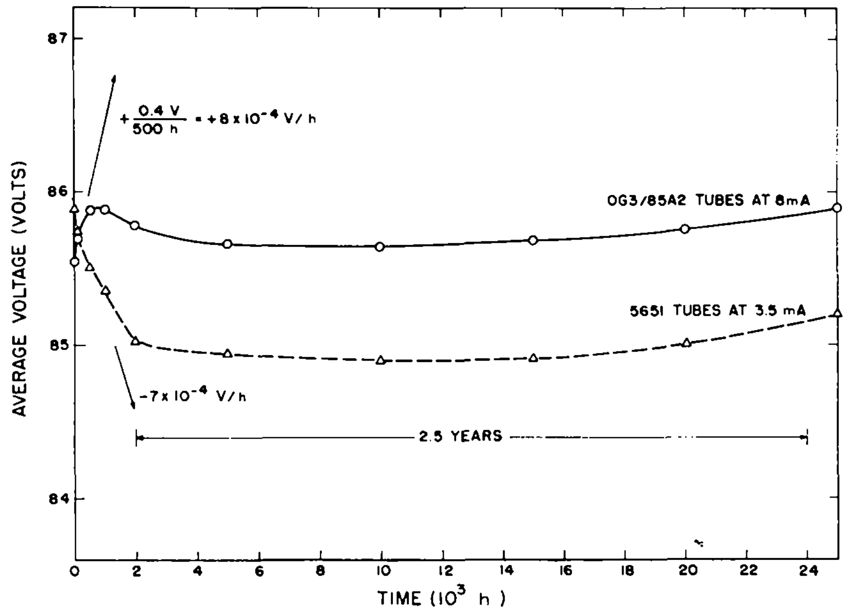

Fig. 1. Averaged and replotted data from W. G. Hoyle's long term tests of four 5651 and five OG3/85A2 gas discharge tubes (ref. [5])).

3. Lifetime Expectancy

The lifetime expectancy of the ordinary filament type radio tube can be and has been debated, but it seems to the author that a figure of 10^4 hours is a reasonable age at which one may expect 50% of the tubes to be useful. The gas discharge tube, however, is probably in a class by itself when longevity is discussed.

[5]) W. G. Hoyle, Long-Term Tests on the Voltage Stability of the Gas-Discharge-Tube Types 5651 and OG3, Rev. Sci. Instr. **27** (1956) 415.

[6]) W. H. Weber, Los Alamos internal report, December 1956.

Under proper conditions the glow tube will probably survive longer than the person who attempts to measure it.

The theoretical work by C. H. Townes[7]) on the sputtering rates in low voltage discharge and the experimental confirmations performed by G. H. Rockwood[8]) for the Western Electric neon tube 313C indicate that the lifetime of this type would be greatly extended by operating at a reduced current. Their data cover the range from 10^4 hours of life at 10 mA current to 4 hours of life at 150 mA. If the tube were to be operated at 2 mA, the extrapolated lifetime is 4×10^3 years. One assumes that a longer lifetime means that the previous observed rates of voltage change with time, due to tube ageing, would be decreased by the increased lifetime ratio. If this is so, a tube might be brought quickly to the relatively stable point as found by Hoyle and then operated at a reduced current for an indefinitely long period of time.

An interesting experiment using the 85A2 tubes would be to compare the voltage drifts with time, say the drift of 20 tubes in series operated at 8 mA with the drift from another series of 20 operated at 2 mA. The voltage drift rate should be reduced by a factor of 100 to 1000 in the 2 mA case, which is about 10^{-5} to 10^{-6} volt/h per tube. It is obvious that these small rates of change can be measured only with the aid of good potentiometer and standard cell techniques, and that the current and temperature of the tubes must be well controlled.

4. Voltage Regulation Considerations

In the usual photomultiplier tube arrangement, the voltages for the various dynodes are obtained from a series resistance voltage divider. In order to stabilize the photomultiplier tube gain, the current through the resistor string is made large compared to any average currents delivered by the photomultiplier tube collector. If the average current is on the order of 1 to 3×10^{-6} A, then the resistor current should be 1 to 3×10^{-4} A or larger. The net load presented to the power supply is, therefore, a constant resistance (within $\pm 1\%$) and the glow discharge regulator will operate in an ideal manner.

It is of interest to consider the simplest type of stabilizer and to estimate the effect of the circuit parameters on the voltage stability or regulation. In fig. 2 we have shown schematically n tubes in series, which provide a voltage ne for the dynode resistor divider R_2. The n tubes are supplied a current i_1, from the unregulated voltage source E, through the current limiting

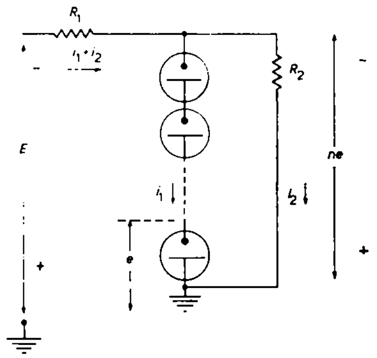

Fig. 2. Basic regulator circuit with n tubes in series.

resistor R_1. The usual precautions, as noted by Benson on pages 30 to 33 of ref. [1]), must be observed in choosing the circuit parameters in order that the tubes will initially "strike" and then operate in the correct current range. The voltage e across one tube can be approximately described for analytical purposes by linear function of the current through the tube:

$$e = a + bi_1 . \qquad (1)$$

A plot of e as a function of i, in the Mullard handbook[3]), for the 85A2, yields the constants $a = 83.1$ V, $b = 300\ \Omega$, for the operating range of 10^{-3} to 10^{-2} A.

Let us define the regulation factor M as

$$M = \frac{\delta E/E}{\delta(ne)/ne} = \frac{\text{relative variation of } E}{\text{relative variation of } ne}, \qquad (2)$$

where δE is the variation of E and $\delta(ne)$ is the variation of ne.

For n tubes, the regulated voltage is $ne = n\,(a + bi_1)$;

$$\therefore \frac{\delta(ne)}{ne} = \frac{b}{e}\,\delta i_1 . \qquad (3)$$

[7]) C. H. Townes, Theory of Cathode Sputtering in Low Voltage Gaseous Discharges, Phys. Rev. **65** (1944) 319.

[8]) G. H. Rockwood, Current Rating and Life of Cold-Cathode Tubes, Trans. Am. Inst. Elec. Engrs. **60** (1941) 901.

Equation (3) demonstrates that the voltage stability is only slightly dependent upon the tube current. For example, for $i_1 = 2 \times 10^{-3}$ A,

$$\frac{\delta(ne)}{ne} = 7 \times 10^{-3} \left(\frac{\delta i_1}{i_1}\right).$$

If we neglect ageing and temperature effects, the variations δi_1 will be caused by the independent variations δE, δR_1 and δR_2, and δi_1 may be computed by the propagation of error law. Thus

$$\delta i_1 = \pm \sqrt{\left(\frac{\partial i_1}{\partial E}\right)^2 (\delta E)^2 + \left(\frac{\partial i_1}{\partial R_1}\right)^2 (\delta R_1)^2 + \left(\frac{\partial i_1}{\partial R_2}\right)^2 (\delta R_2)^2}. \tag{4}$$

The current i_1 is derived from the two voltage loop equations for fig. 2, namely,

$$E = R_1 (i_1 + i_2) + n (a + b i_1),$$
$$n (a + b i_1) = i_2 R_2. \tag{5}$$

Eliminating i_2 and solving for i_1 gives

$$i_1 = \frac{R_2 E - na (R_1 + R_2)}{R_1 R_2 + nb (R_1 + R_2)}. \tag{6}$$

Applying eq. (4) to eq. (6) yields a rather cumbersome expression for δi_1:

$$\delta i_1 = \pm \frac{n R_1 R_2}{D^2} \sqrt{\left(\frac{D}{n R_1}\right)^2 (\delta E)^2 + \left[E\left(\frac{R_2}{n} + b\right) - a R_2\right]^2 \left(\frac{\delta R_1}{R_1}\right)^2 + [Eb + a R_1]^2 \left(\frac{\delta R_2}{R_2}\right)^2}, \tag{7}$$

where $D = R_1 R_2 + nb (R_1 + R_2)$.

Fortunately, if the tube is to work as a regulator, it is required that R_1 and R_2 be large compared to the total dynamic resistance of the tubes, and eq. (7) may be simplified. That is,

$$R_1 \gg nb, \quad R_2 \gg nb. \tag{8}$$

Therefore $D \approx R_1 R_2$,

also $E\left(\frac{R_2}{n} + b\right) - a R_2 \approx \frac{R_2}{n}(E - na)$,

and $Eb + a R_1 \approx a R_1$

for reasonable values of E. With the approximation equation (8), eq. (7) reduces to

$$\delta i_1 = \pm \frac{1}{R_1} \sqrt{(\delta E)^2 + (E - na)^2 \left(\frac{\delta R_1}{R_1}\right)^2 + \left(na \frac{R_1}{R_2}\right)^2 \left(\frac{\delta R_2}{R_2}\right)^2}.$$

If we let $(E - na) = kE$, where

$$0 < k < 1,$$

then

$$\delta i_1 = \pm \frac{E}{R_1} \sqrt{\left(\frac{\delta E}{E}\right)^2 + k^2 \left(\frac{\delta R_1}{R_1}\right)^2 + (1 - k)^2 \left(\frac{R_1}{R_2}\right)^2 \left(\frac{\delta R_2}{R_2}\right)^2}. \tag{9}$$

Equation (9) has its simplest form when $k = \frac{1}{2}$.

In a well designed power supply, one would try to equalize the terms under the square root sign. For the elementary circuit of fig. 2, when moderately stable resistors are used ($\delta R/R = \pm 10^{-3}$), the input voltage variation $\delta E/E$ will have the largest effect. Therefore

$$\delta i_1 = \pm \frac{\delta E}{R_1} \tag{9'}$$

when

$$\frac{\delta R_1}{R_1} < \frac{\delta E}{E}, \quad \frac{\delta R_2}{R_2} < \frac{\delta E}{E}, \quad R_1 \approx R_2, \tag{10}$$

a result which could have been obtained easily by inspection of eq. (6) when conditions (8) and (10) are applied. The regulation factor M follows by combining eqs. (9'), (5), (3) and (2):

$$M = \frac{\delta E/E}{\delta(ne)/ne} = \left(1 - \frac{ne}{E}\right) \frac{e}{b} \left(\frac{1}{i_1 + i_2}\right). \tag{11}$$

In a practical power supply for 1700 V, it is interesting to evaluate M for various values of E. Let

n = 20 tubes (85A2),
ne = 1700 volts,
$i_2 = 0.2 \times 10^{-3}$ A = load current,
$i_1 = 2.0 \times 10^{-3}$ A = tube current,
R_2 = load resistor $\approx 8.5 \times 10^6\ \Omega$.

Equation (11) is therefore

$$M = \left(1 - \frac{1700}{E}\right) 126.$$

A plot of M and the necessary resistance R_1, as functions of E, is shown in fig. 3. When $E = \infty$, $M_{max} = 126$. When $E = 2ne$, $M = \frac{1}{2} M_{max} = 63$, and $k \approx \frac{1}{2}$ since $a \approx e$. When E is furnished by a simple high voltage rectifier unit, the relative variations of E will be the same as the relative variations in power line voltage. Suppose $\delta E/E = \pm 10\%$, corresponding to a line voltage of 115 ± 10 V a.c.; then for

$M = 63$, $\delta e/e = \pm 0.16\%$, and the photomultiplier tube gain[9]) would vary about $\pm 1\%$. If one needs more regulation, two stabilizers should be joined in series, with $2n$ tubes in the first, supplying $2ne$ volts for n tubes in the second. The combined regulation should be M^2 or about 4000. However, the best results from the compound stabilizer will be obtained only by controlling the temperature, recognizing the ageing phenomena, and using resistors of high stability. One example of a compound stabilizer has been built by J. K. Bair *et al.*[10]).

5. Present Design

Using presently available parts, we have constructed a number of glow discharge tube regulated power supplies which operate photomultiplier tubes with a 5×10^6 ohm dynode voltage divider. The supplies consist of a voltage source E rated at $E = 5400$ at 5×10^{-3} A (a packaged unit) feeding twenty 85A2 tubes through a $1.5 \times 10^6\,\Omega$, 10 W resistor. The regulated voltage is 1685 V and varies slightly from unit to unit. A circuit schematic is shown in fig. 4. It will be noticed that several additions have been made to the basic circuit (fig. 2) discussed above. Starting resistors, placed across most of the 85A2 tubes, reduce the necessary striking voltage for the 20 tubes in series to about (1685 + 40) V; otherwise, without the resistors, the striking voltage is about (1685 + 500). As the voltage builds up across the tubes, first the open pair strike, then the pair across R_1, then across R_2, the process continuing until the last pair is reached when the tube across R_9 lights, then finally R_{10}. The capacitor C not only helps to reduce residual noise and rectifier ripple, but also limits the rate of voltage build up. When $C = 4 \times 10^{-6}$ farad, the short term fluctuations (< 1 second) are less than 10^{-3} volt. A measured regulation factor $M = 80$ agrees roughly with the results predicted by fig. 3. R_{11}, R_{12} and R_{13} should be good quality high voltage resistors. R_{12} protects the 85A2 from a current surge from C when the tubes initially strike. Resistor R_{13} protects the

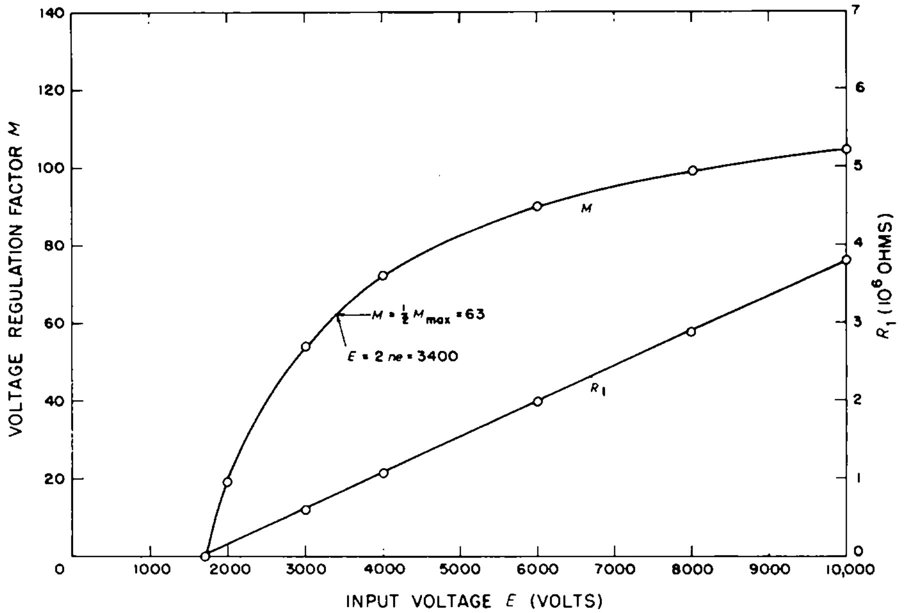

Fig. 3. Computed voltage regulation and series resistance R_1 for 1700 V output with twenty 85A2 tubes. Load resistance $= 8.5 \times 10^6\,\Omega$. Limit for $E = \infty$. $M_{max} = 126$.

[9]) G. A. Morton, Photomultipliers for Scintillation Counting, RCA Rev. **10** (1949) 525.

[10]) J. K. Bair *et al.*, An Extremely Stable Power Supply for Scintillation Counter Use, NEPA Division Report NEPA 1265-Ser-8 (January 20, 1950).

user of this supply from the energy stored in C. The high voltage at the output plug can be short circuited without damage to the circuitry.

A very rough attempt was made to measure the voltage drift of twenty 85A2 tubes in series, operating at 2 mA under constant current and temperature conditions. The average drift rate may have been as low as 10^{-5} V/h per tube over a period of 10 days. We concluded that operating the tubes at 2 mA instead of 8 mA definitely decreases the ageing rate, but quantitative results await better and more patient measurements.

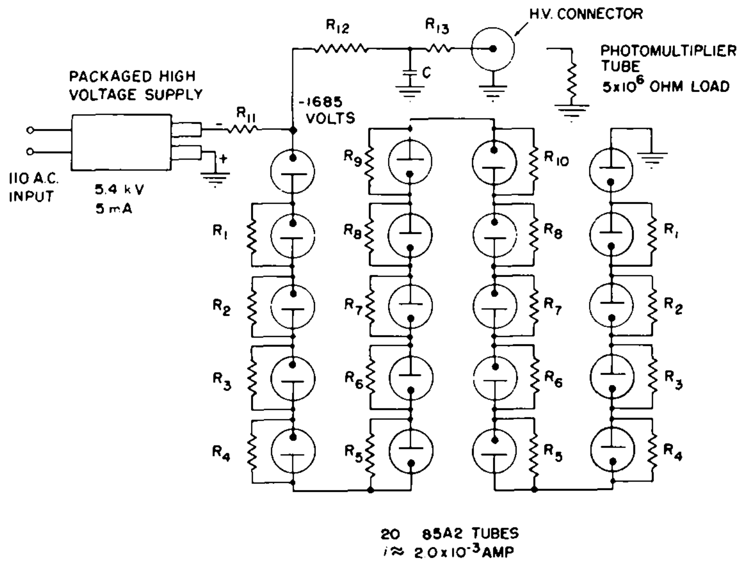

Fig. 4. Glow discharge regulator for photomultiplier tube voltage. $R_1 = 3.0$; $R_2 = 2.4$; $R_3 = 2.0$; $R_4 = 1.6$; $R_5 = 1.3$; $R_6 = 1.1$; $R_7 = 0.91$; $R_8 = 0.75$; $R_9 = 0.51$; $R_{10} = 0.39$; $R_{11} = 1.5$, 10 W; $R_{12} = 0.05$, 1 W; $R_{13} = 0.05$, 1 W; $C = 1$ to 4×10^{-6} F, 2000 V. Note: Resistance in $10^6\ \Omega$. Resistors $\frac{1}{2}$ W except as noted.

6. Conclusions

These notes are intended as a guide to those who contemplate building regulated power supplies for use with photomultiplier tubes, or for those who have worried about the complexity and cost of some commercial power supplies for the same purpose. We have not said anything that is new, or that is not available in the current literature. It has been demonstrated that the 85A2 tube has a very small voltage drift rate when operated at $\frac{1}{4}$ to $\frac{1}{5}$ its maximum rated current, and the question has been raised as to how stable the tube is and what its lifetime is at these reduced currents. The expected variations of the regulated voltage due to changes in line voltage and resistance variations in the circuit have been discussed. Finally, a practical circuit for regulating approximately 1700 V at about 0.1 to 0.2% for ordinary line voltage variations has been outlined.

Acknowledgments

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