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Design and Operational Characteristics of Thoriated Tungsten Filaments in High Power Valves

by J. ZIEGLER, B.Sc.

The thoriated tungsten cathode is described, and the nature of the physical processes associated with it indicated. An account is given of a typical method of arriving at a design of a filamentary thoriated tungsten cathode for a valve, and a method is developed for solving the problem of making adjustments to a design for any given set of compatible requirements. Operating practices are discussed, in relation to both the strong dependence of emission life upon applied filament voltage, and the influence of traces of residual gas.

Introduction

The chief properties of thoriated tungsten responsible for its wide use as an electron source in electron tubes of high power are, firstly, its good emission efficiency in terms of milliamps per watt when compared to pure tungsten, and secondly, its ability to withstand high anode voltages, when compared to the alkaline earth oxide cathode as used in smaller valves.

Thoriated tungsten has been used as an emitter for many years and the principles of its application are well known. It consists of tungsten in which is dispersed a small quantity of thoria—of the order of 1% or 2% by weight. Because of its mechanical properties, it is usual to employ it in the form of drawn wires of round section. The wire is partially converted to di-tungsten carbide (W_2C), commonly by heating the wire to about 2300°K in an atmosphere containing a hydrocarbon gas or vapour such as ethylene, toluene, xylene, etc., the step being referred to as carburizing. A carburized wire has a core of thoriated tungsten and an outer shell of di-tungsten carbide in which thoria is dispersed. See Figs. 1 and 2.

A thoriated tungsten emitter is usually operated at a temperature in the vicinity of 2000°K (1727°C), when a good emission life is realised together with a reasonable emission efficiency. The emission efficiency of pure tungsten is about 10 ma/watt: that of thoriated tungsten is some 100 ma/watt, whilst that of the alkaline earth oxide cathode is in the order of 1000 ma/watt. The emission life depends upon both the amount of carbide and the operating temperature. Figs. 3 and 4 describe this dependence as found by experiment. Individual valve lives would actually be expected to show rather wide statistical divergences from the curves of Fig. 3. This is discussed elsewhere[1], it being stated that these data " almost certainly underestimate the life that can be obtained from modern cooled-anode valves" : The curve of Fig. 4 is drawn from data available [1, 2].

Physical Processes

It is generally accepted that the lowering of the work function of tungsten by the addition of thoria to the wire is caused by the presence of a layer, perhaps less than a complete monolayer, of thorium atoms on its surface. This thorium is produced by chemical dissociation of the thoria within the wire, tungsten carbide acting as the reducing agent, and probably takes place principally at temperatures reached during manufacture[3]. It has been suggested[1] that it may also take place slowly and continuously at filament operating temperature during the service life of the valve, the thorium diffusing to the surface. Continuous replenishment of thorium at the surface, at least by diffusion, would be necessary in order to replace that slowly removed from the surface by evaporation and positive ion bombardment. The rates of dissociation, diffusion, and removal as well as the quantity of thoria stored in the wire are such that, for operation within the range 1950-2050°K, the end of useful emitting life of a thoriated tungsten filament is not likely to be governed by the original amount of thoria.

The fact that the presence of carbide not only produces, but is necessary to maintain the lowering of the work function of tungsten, conferred by the addition of thoria, was originally explained[1, 2, 3] by attributing to the carbide layer the action of resisting the outward diffusion of thorium, thus dispensing thorium at a rate sufficiently slow to prevent its exhaustion within a reasonable life span. It would appear to have been demonstrated[4] that this is not the explanation: that the carbide acts rather as a preferred target for attack by residual gas left in the valve after even the most careful pumping schedule, in this way tending to protect the thorium layer. Thus, the emission life of a thoriated tungsten emitter, upon which information is given in Fig. 3, comes to an end when substantially all of the protective shell of di-tungsten carbide has been converted back to tungsten. Valves with thoriated tungsten emitters which have reached the end of their emission life have little or no carbide left on the filament.

Jenkins and Trodden[4] have investigated reactions between W_2C and various residual gases. One is struck by the thought that residual gases would be responsible for converting to tungsten many milligrams of W_2C in a typical valve. It is inconceivable that sufficient mass of gas be available for this in a modern high power valve without supposing a recurrent cycle of some sort. On this supposition, a gas capable of reacting in this way need have only a minute pressure in order eventually to remove all the combined carbon from the filament.

A question arises as to the nature of the gas and the reaction cycle. Data[4] indicate that the three gases O_2, CO_2 and H_2O react with W_2C to form W and CO, and H_2 as well in the case of H_2O. It is tempting to surmise that, under conditions obtaining in the valve, hydrogen and carbon monoxide may react to form water vapour and free carbon. One could then posit the cycle:

$$\begin{tikzcd} H_2O + W_2C \arrow[r] & 2W + \underbrace{CO + H_2} \arrow[d] \\ & H_2O + C \arrow[ul] \end{tikzcd}$$

the carbon being deposited on various surfaces in the vacuum.

Raising the temperature of a filament would be expected to increase the rates of diffusion and removal of thorium as well as the rates of the several chemical reactions. All of these effects would result in reduced life, and Fig. 4 indicates the extent of this reduction.

Lowering filament temperature would, conversely, increase life, at least for moderate temperature changes. However, if the temperature is reduced sufficiently, one might question whether the changed rates of replenishment and removal of thorium would maintain enough of it on the surface over a long period to preserve the efficiency of electron emission. The indications from experience are that the work function does indeed tend to increase steadily with time in such a case: thus one cannot rely upon extrapolating Fig. 4 to lower temperatures to predict increased life, and a valve so run may gradually lose much electron emission while retaining some W_2C. It would be expected that treatment at a suitably elevated temperature, such as used in manufacture to form the thorium layer, would then re-establish the emission, and this, too, agrees with experience.

Design

At one time, it was customary to design a thoriated tungsten emitter empirically. However, the method described below (or variations of it) is well known and would now be used almost universally[1].

A filament in this context refers to a cathode consisting of either one strand of wire, or several connected in parallel: choice of the number

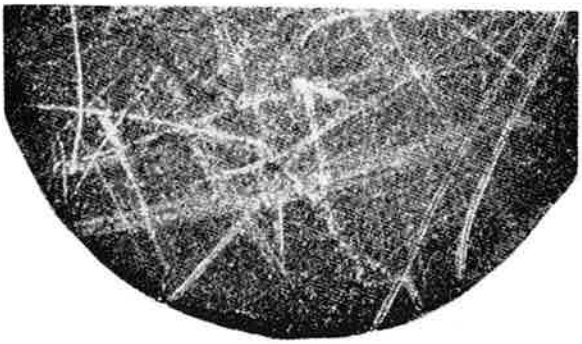

Fig. 1—Section of part of an uncarburised thoriated tungsten wire. This photograph, and that of Fig. 2 have been retouched to eliminate the mounting medium. Edge detail is therefore impaired. The long white lines are scratches due to imperfect polishing of the specimens.

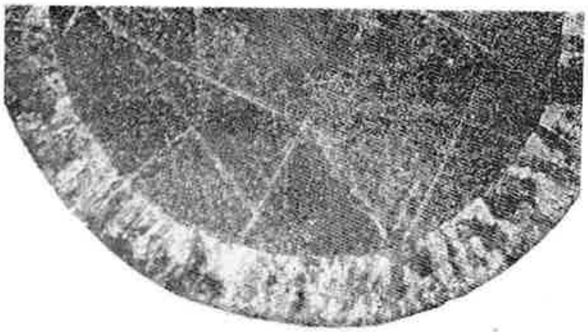

Fig. 2—Section of part of a carburised thoriated tungsten wire showing layer of W_2C.

of strands will be influenced by such factors as constructional requirements, valve geometry, and the desired filament rating.

There are six principal quantities to be considered, viz.

the voltage applied to a strand,	E volts,
the current in a strand,	I amps,
the radius of a strand,	r cm,
the length of a strand,	L cm,
the operating temperature,	T°K and
the fraction of area of cross section converted to W_2C,	c.

One begins a filament design knowing the maximum instantaneous cathode emission required by the design of the valve. One then allows a safety factor of perhaps four or five times this maximum emission figure. Reference to information such as that contained in the curve of Fig. 5 yields the necessary wattage rating to achieve the emission desired. This curve describes total electron emission values, and represents average figures. As noted, rather wide statistical divergences from it are to be expected. A safety factor of the magnitude allowed is necessary because the work function of a substance, upon which its electron emission depends, is determined by the outermost layer of atoms at its surface. The work function of a composite material like thoriated tungsten is therefore not a quantity that lends itself to being reproduced with precision from one sample to the next.

It is sufficiently accurate to assume that all of the electrical power dissipated in the filament strand is radiated from its surface in accordance with the Stefan-Boltzmann radiation equation.

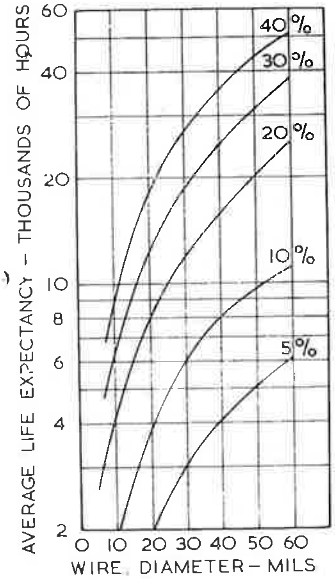

Fig. 3—Average life expectancy at 2000°K of carburised thoriated tungsten filaments as a function of wire diameter and the percentage of area of cross section converted to W_2C. This is based on life test data[2].

One can then write

$$EI = S\epsilon T^4 A = 2\pi S\epsilon r L T^4 \qquad (1)$$

where S = Stefan-Boltzmann constant = $5{\cdot}73 \times 10^{-12}$ watt cm^{-2} degree^{-4},

ϵ = power emissivity of the surface, taken[6] as 0·35 for carburized thoriated tungsten near 2000°K,

T = temperature in degrees K, and

A = surface area of a strand.

We may assume an operating temperature of 2000°K. Reference to Figs. 3 and 4 will lead to a choice, based on considerations of life, of the area percentage of carbide to be used in conjunction with wire of a given diameter.

It may be questioned why substantially all of the wire is not customarily converted to di-tungsten carbide, as this would result in the best life obtainable from wire of a given size operating at a given temperature. Whilst there would be technological difficulties in attaining the proper type and formation of tungsten carbide, the principal objection is that as the percentage of carbide increases the wire becomes more and more brittle, to the point where it becomes impracticable to transport the finished valve.

The next step is to choose the voltage rating, E, of the filament strand. This also fixes its hot resistance, and one may then relate this to the area percentage of carbide that will be used and the conductivities at 2000°K of thoriated tungsten and di-tungsten carbide[1].

Making

σ_f = " average " conductivity measured in the axial direction of a carburized filament strand,

σ_W = conductivity of thoriated tungsten, and

σ_c = conductivity of W_2C,

and using subscripts to indicate temperature in degrees Kelvin, there is the relation

$$\sigma_{f_{2000}} = \sigma_{W_{2000}} - c(\sigma_{W_{2000}} - \sigma_{c_{2000}}) \qquad (2)$$

One then has

$$E/I = L/(\pi r^2 \sigma_{f_{2000}}) \qquad (3)$$

for the carburized filament strand at 2000°K.

Values quoted for the conductivities of thoriated tungsten and of W_2C are[1] (in units of 10^3 ohm^{-1} cm^{-1})

$\sigma_{c_{2000}} = 8{\cdot}48$; $\sigma_{W_{2000}} = 17{\cdot}9$; $\sigma_{c_{293}} = 12{\cdot}5$; $\sigma_{W_{293}} = 182$.

Solving Eqs. (1) and (3) simultaneously yields the length and diameter of the filament.

The method described is approximate and ignores various corrections, but does lead to results that are quite satisfactory in practice. It is, however, worth digressing to consider one point ignored in the above discussion : the cooling of the ends of the filament strand by thermal conduction to their supports. Notice that the designed operating temperature and percentage of carbide are derived from the application of Ohm's law to the filament strands, thus yielding some sort of average temperature and average carbide percentage. The carbide percentage is customarily calculated from resistance readings of the filament wire taken before and after carburizing. Now, referring to Fig. 4, it is clear that the life of the filament is a very rapidly changing function of the temperature, and the temperature must vary along the length of the wire due to end cooling effects. Thus, one might expect the designed averaged temperature to yield a poor prediction of the life of the filament.

However, during carburizing, when the wire is heated by passage of current, the centre of the wire is also hotter than its ends. This leads to a greater rate of combination of carbon with tungsten, and one finds that the shell of di-tungsten carbide in the middle of a strand is thicker than towards the ends. Thus there is more carbide in the hotter part of the wire, from which it also disappears more rapidly in service, the final result being that the variation in temperature tends to be offset.

Whilst the above method yields a good basic design, it is none the less true that small adjustments may be necessary: for example, to allow for temperature effects due to the close proximity of filament strands to one another, or to take into account manufacturing tolerances. Such adjustments may be carried out empirically, and it is usual to do so.

Variations in Design

Sometimes simultaneous adjustments must be made in several filament parameters whilst leaving others fixed. It might happen, for example, that one wishes to reduce the filament operating temperature whilst increasing the carbide percentage, and perhaps also making provision for the use of a new batch of filament wire having a slightly different diameter. In accommodating these variations, it might be necessary to keep the filament rated voltage unchanged, since it is usual to operate filaments at constant voltage, whilst the filament wire length and current at the rated voltage may be allowed to vary. An empirical approach to a solution of this sort of problem consumes a great deal of time and expense, whilst on the other hand it is not convenient to use the design equations given earlier.

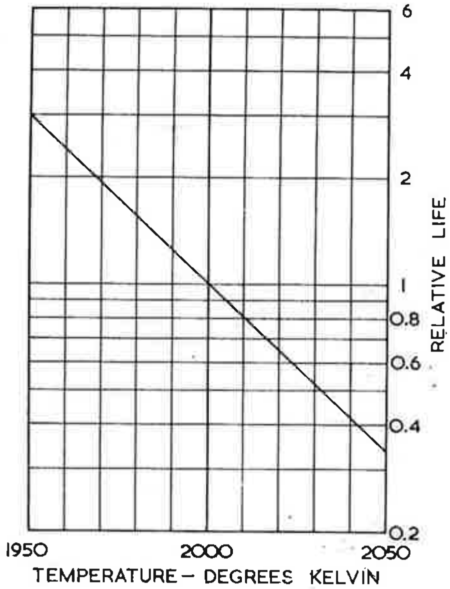

Fig. 4—Relative life as a function of temperature for carburised thoriated tungsten, based on measured rates of loss of carbon.

A convenient method for making design adjustments is given below.

One begins by writing

$$W = EI/2\pi rL \qquad (4)$$

where W = radiated watts/cm².

Also

$$W \times A = E^2/\rho = \pi r^2 E^2 \sigma_f / L \qquad (5)$$

where ρ is the wire resistance.

Whence

$$W = rE^2\sigma_f/2L^2 \qquad (6)$$

Eqs. (4) and (6) may be written:

$$\log W = \log E + \log I - \log r - \log L - \log \pi - \log 2 \qquad (7)$$

and

$$\log W = \log r + 2\log E + \log \sigma_f - 2\log L - \log 2 \qquad (8)$$

It is then readily shown that

$$\frac{\Delta W}{W} \approx \frac{\Delta E}{E} + \frac{\Delta I}{I} - \frac{\Delta r}{r} - \frac{\Delta L}{L} \qquad (9)$$

and

$$\frac{\Delta W}{W} \approx \frac{\Delta r}{r} + \frac{2\Delta E}{E} + \frac{\Delta \sigma_f}{\sigma_f} - \frac{2\Delta L}{L} \qquad (10)$$

where Δ signifies a finite increment.

The operating temperature and percentage of carbide together determine the conductivity σ_f of the filament. One may now plot relative variations in σ_f as a function of both the temperature and the carbide percentage, assuming knowledge of conductivities and their temperature coefficients. This has been done in Fig. 6. On the same

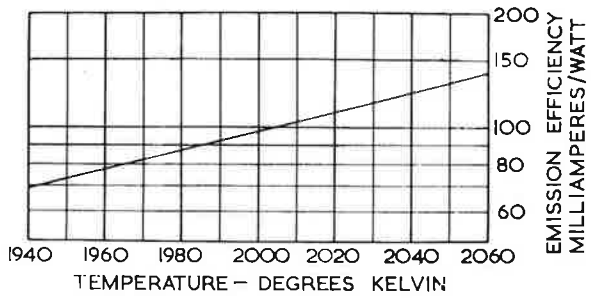

Fig. 5—Emission efficiency of carburised thoriated tungsten as a function of temperature. Drawn from values quoted[5] and the value for ϵ (Equ. 1) for W_2C given elsewhere[6].

figure has been plotted relative variations in the thermal emissivity W as a function of temperature. It is a convenient circumstance that the latter, over the fairly narrow temperature range considered, approximates to a straight line, and is so drawn.

The graph of Fig. 6 is constructed in the following manner :

(a) Changes in W with temperature are calculated from Eq. (1).

(b) Eq. (2) is used for calculating changes in σ_f with percentage of carbide, with the values given for above σ_W and σ_c.
For calculating changes in σ_f with temperature, the temperature coefficient of σ_W is taken as $-6{\cdot}05\%$ per 100°K (from tabulated data[7]) ; the temperature coefficient of σ_c is estimated as $-2{\cdot}35\%$ per 100°K.

(*c*) For purposes of establishing the curves, reference levels for temperature and C% are taken as 2000°K and 20% respectively. However, for purposes of use, it is sufficiently accurate to use any typical value as reference.

One may now consider relative variations, expressed for convenience as percentages, in the approximate equalities of Eqs. (9) and (10). Any changes in W and σ_f resulting from changes in the temperature or the percentage of area of cross section converted to W_2C (C%) may be read as percentages from Fig. 6.

An example of the type of problem mentioned at the beginning of this section may be used by way of illustration.

Example

It is required that the temperature be lowered 10°K, and C% is to increase 5%, while $\Delta r/r = -4\%$. ΔE must be zero.
Find $\Delta L/L$ and $\Delta I/I$.
From Fig. 6,

(a) for $\Delta T = -10°K$, the interval AB represents $\Delta W/W = -2{\cdot}0\%$

(b) for $\Delta C\% = +5\%$, the interval CO represents $\Delta\sigma_f$ with temperature unchanged. When, simultaneously, $\Delta T = -10°K$, the interval DB represents the required value of $\Delta\sigma_f/\sigma_f$, i.e., $-2{\cdot}4\%$.

Thus from Eq. (10)

$$\Delta L/L \approx -2{\cdot}2\%$$

and from Eq. (9)

$$\Delta I/I \approx -8{\cdot}2\%$$

Operating Practice

As mentioned, it is usual to design a thoriated tungsten filament to operate near 2000°K. In some applications, pulse modulators for example, high emission efficiency can assume great importance, and emission life may be sacrificed to achieve it by raising the operating temperature a hundred degrees or more above that value. However, the figure of 2000°K as a design figure yields reasonable life whilst being safely above temperatures at which the work function tends to increase gradually.

It may be verified from the data presented that a change of about 4% in filament voltage (e.g., a fall) will change the temperature by 30°K (fall), leading to an emission change of about 20% (fall) and a life change by a factor of 2 (rise).

Thoriated tungsten types are mostly intended for operation at constant voltage on the filament,

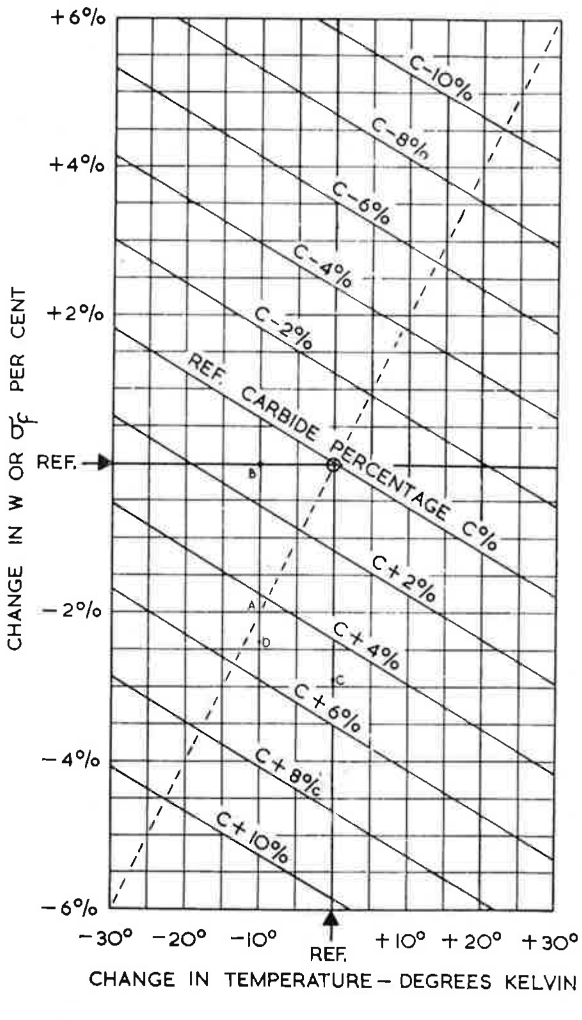

Fig. 6—Relative changes in thermal radiant emissivity W (dashed line) and filament conductivity ϱ_f (solid lines) as functions of changes in temperature and carbide percentage. The points and line marked "REF" are reference levels representing any starting point to which changes are to be referred.

since this suits circuit economy, and a tolerance of ±5% is usually given in order to cater for operation without a well regulated supply. For operation during standby periods manufacturers generally recommend reduction of filament voltage by 5% from the nominal value. In fact it is usually possible to operate the filament at this reduced voltage while the valve is drawing its normal anode current, because the emission reserve of the filament will permit cooling to the degree implied.

Clearly, if one decides, in the interest of greatly improved life, to operate near the lower limit of filament voltage, good regulation and an accurate measuring instrument are called for. Voltage measurements must be made at the valve filament terminals, the points to which the rating is referred.

It might be questioned whether it would be feasible to reduce the filament voltage below the lower rated limit, to the point where circuit performance is just not affected. Thus one might reduce filament voltage in a transmitter until changes in anode current or distortion begin to evidence themselves, then raise the voltage, say, 3% above that level. Such an operation, besides calling for precision, would obviously result in a voltage dependent in part upon both the filament characteristics of the individual valve and the peak instantaneous cathode current called for by the transmitter.

Such a plan will sometimes work. However, as discussed in the Physical Processes Section, experience indicates that the desired benefit may not ensue due to gradual deterioration of the thorium layer.

It is mentioned earlier that residual gas in the valve plays a key part in the process culminating in loss of emission from the filament. It would be expected that anything tending to raise the pressure of this gas would thereby shorten the life of the valve, and this is indeed so. While space current is being drawn, gas molecules tend to become ionised and in this condition are much more likely to be gettered (sorbed) by various surfaces in the valve. During periods when no high voltages are applied to the valve the reverse process, desorption, takes place, and the pressure of the residual gas tends to rise slowly. It is for this reason that it is often recommended by manufacturers that thoriated tungsten types in storage be operated periodically, if not near their ratings, at least by drawing appreciable space current with some hundreds of volts applied to some electrode, to encourage ionisation, sorption, and thus reduction in pressure of the residual gas. (It should be remarked that the pressures involved are usually well below those at which an ionisation glow would be visible in the valve.) Such "exercising" would commonly be recommended for repetition at intervals of three to six months.

The foregoing is pertinent to the consideration of a practice sometimes adopted; that of running a standby transmitter with filaments alight but with high tension off, to provide rapid changeover in the event of a fault in the main transmitter. Whilst reduction of filament voltage in such a case has been discussed, it is also to be considered that gas desorption takes place more rapidly from a heated surface: with internal surfaces heated by the filament the effects that take place during normal storage are accelerated. In such a situation it is better practice to apply high tension and draw space current for a period each day rather than each week or some longer interval.

Conclusion

The design of a thoriated tungsten emitter can be carried out readily by using the customary methods, such as the one described. Adjustments to a basic design can be achieved using the method presented here. A successful design represents a delicate balance between a number of closely related factors, some of which change quite rapidly with others. In particular, the emission life of a thoriated tungsten emitter is very sensitive to the applied voltage across the filament ends.

Whilst the achieving of a good average filament life from a valve design is largely in the hands of the manufacturer, the user can, by careful supervision, obtain better average life than if he were content to use the valve at its nominal rated filament voltage. Suitable exercising of valves in storage, and of those subjected to protracted periods of operation of the filament without high tension, is also advisable in the interests of good life.

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SUPER RADIOTRON 25LP4 PICTURE TUBE

The 25LP4 is a large-screen, directly-viewed glass picture tube having an aluminised screen 20⅞″ by 16⅜″, with a minimum projected area of 327 square inches. It employs 110°-angle magnetic deflection and low-voltage electrostatic focus. An integral protective plate glass window bonded to the face of the tube eliminates the need for a separate safety-glass window in the receiver. The 25″ tube, by providing an increased horizontal screen dimension, permits the presentation of a picture having an aspect ratio approaching 3:4.

GENERAL

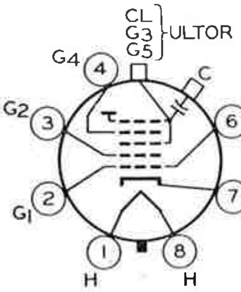
Heater Voltage	6.3 volts
Heater Current	0.6 amp
Direct Interelectrode Capacitances:	
Cathode to all other electrodes	5 pf
Grid 1 to all other electrodes	6 pf
External conductive coating to anode:	
Maximum	2500 pf
Minimum	2000 pf
Faceplate and Protective Panel	Filterglass
Light Transmission	40%
Phosphor	Aluminised P4 Sulphide
Fluorescence	White
Phosphorescence	White
Focusing Method	Electrostatic
Deflection Method	Magnetic
Deflection Angles (approx.):	
Diagonal	110°
Horizontal	100°
Vertical	84°

Tube Dimensions:			
Overall Length	16.310	±0.375	inches
Greatest Width	22.360	±0.125	inches
Greatest Height	18.080	±0.125	inches
Diagonal	25.438	±0.125	inches
Neck Length	5.437	±0.125	inches

Screen Dimensions (min.):	
Horizontal	20.875 inches
Vertical	16.375 inches
Diagonal	24.250 inches
Area	327 sq. in.
Electron Gun	Unipotential
Bulb	C204 EXP. NO. 1
Bulb Contact	Jedec J1-21
Base	Jedec B7-183

SOCKET CONNECTIONS

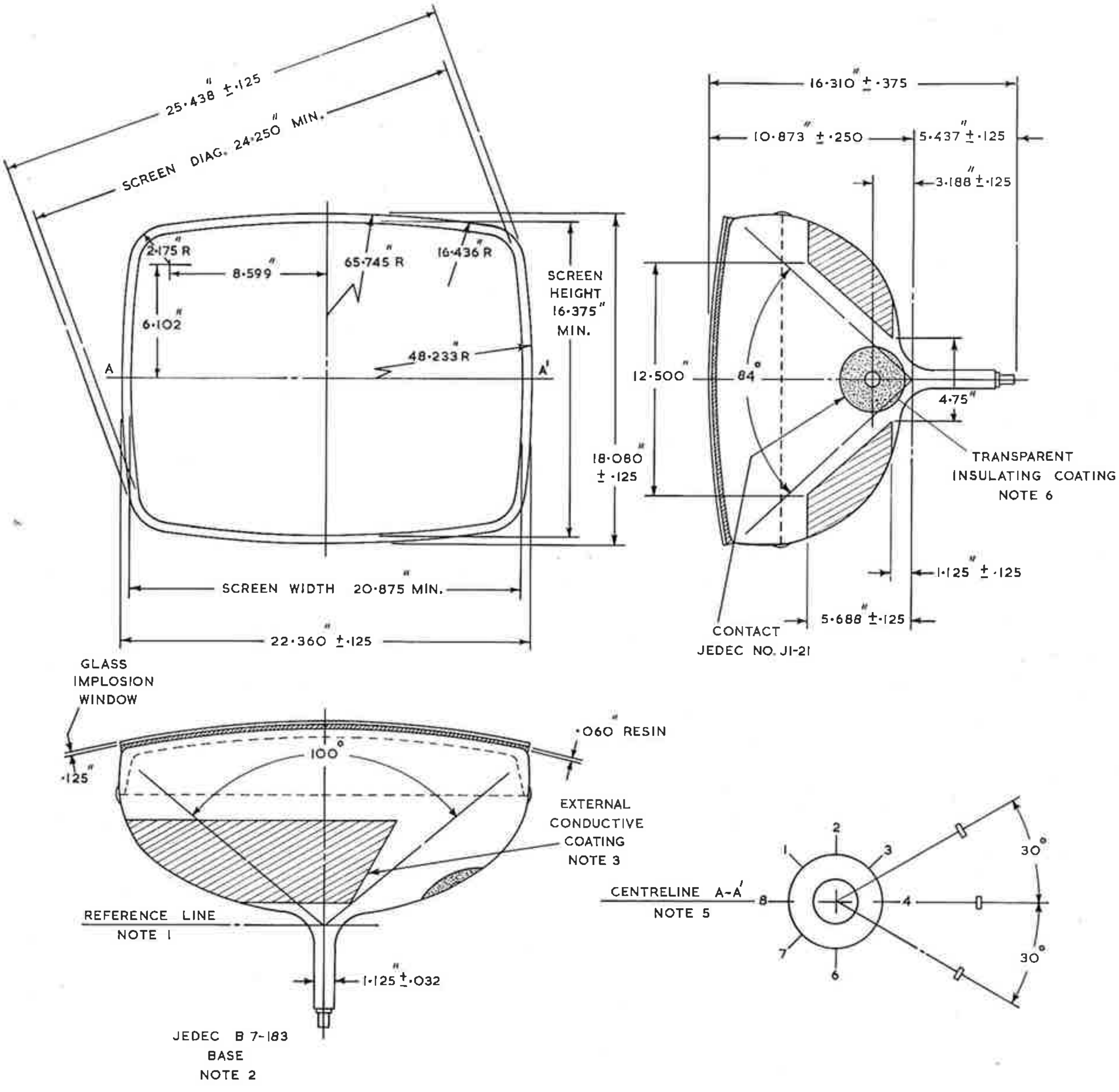
Pin 1—Heater
Pin 2—Grid No. 1
Pin 3—Grid No. 2
Pin 4—Grid No. 4
Pin 5—Blank
Pin 6—Grid No. 1
Pin 7—Cathode
Pin 8—Heater
Bulb Contact—Anode



RATINGS, DESIGN MAXIMUM SYSTEM

(Unless otherwise specified, voltage values are positive, and measured with respect to cathode)

Maximum Anode Voltage	22,000 volts
Minimum Anode Voltage	12,000 volts
Maximum Grid No. 4 Voltage	+1100, —550 volts
Maximum Grid No. 2 Voltage	550 volts
Minimum Grid No. 2 Voltage	200 volts
Grid No. 1 Voltage:	
Maximum Negative Value	—154 volts
Maximum Negative Peak Value	—220 volts
Maximum Positive Value	0 volts
Maximum Positive Peak Value	2 volts



Heater Voltage:	
Maximum	6.93 volts
Minimum	5.67 volts
Heater Current at 6.3 Volts	0.6 amp
Maximum Heater-Cathode Voltage, Heater Negative with respect to Cathode:	
During Warm-up, 15 secs	450 volts
After Warm-up Period	200 volts
Maximum Heater-Cathode Voltage, Heater Positive with respect to Cathode	200 volts

TYPICAL OPERATION, GRID DRIVE SERVICE

(Unless otherwise specified, all voltage values are positive with respect to cathode)

Anode Voltage	18,000 volts dc
Grid No. 4 Voltage*	0-400 volts dc
Grid No. 2 Voltage	400 volts dc
Grid No. 1 Voltage	—36 to —94 volts dc

TYPICAL OPERATION, CATHODE DRIVE SERVICE

(Unless otherwise specified, all voltage values are positive with respect to Grid No. 1)

Anode Voltage	18,000 volts dc
Grid No. 4 Voltage*	0-400 volts dc
Grid No. 2 Voltage	400 volts dc
Cathode Voltage	36 to 78 volts dc

MAXIMUM CIRCUIT VALUE

Grid No. 1 Circuit Resistance	1.5 megohms

* The grid No. 4 (or grid No. 4 to grid No. 1) voltage required for optimum focus of any individual tube will be a value between 0 and 400 volts independent of anode current. It will remain essentially constant for values of anode (or anode to grid No. 1) voltage and grid No. 2 (or grid No. 2 to grid No. 1) voltage within the ranges shown for these items.

NOTES

NOTE 1. Yoke Reference Line is determined by plane surface of flared end of JEDEC Reference Line Gauge No. 126 when seated on funnel of tube. With minimum neck length tube, the PM centring magnet should extend no more than 2¼″ from Yoke Reference Line.

NOTE 2. Lateral strains on the base pins must be avoided. The socket should have flexible leads permitting movement. The perimeter of the base wafer will be inside a 1¾″ diameter circle concentric with the tube axis.

NOTE 3. External conductive coating forms supplementary filter capacitor and must be grounded.

NOTE 4. Neck diameter may be a maximum of 1.168″ at the splice.

NOTE 5. Base pin No. 4 aligns with centreline A-A′ within 30° and is on the same side as anode contact J1-21.

NOTE 6. To clean this area, wipe only with a soft, dry lintless cloth.

SUPER RADIOTRON
11LP4
PICTURE TUBE

The 11LP4 is a directly-viewed glass picture tube having an aluminised screen 9″ by 7⅛″, with a minimum projected area of 60 square inches. It employs 110°-angle magnetic deflection and low-voltage electrostatic focus. The screen is tinted to improve contrast under conditions of high ambient lighting, making the tube very suitable for portable TV receivers.

GENERAL

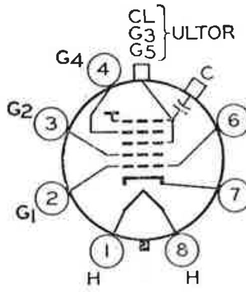
Heater Voltage	6.3 volts
Heater Current	0.3 amp
Direct Interelectrode Capacitances:	
Cathode to all other electrodes	5 pf
Grid 1 to all other electrodes	6 pf
External conductive coating to anode:	
Maximum	600 pf
Minimum	400 pf
Faceplate and Protective Panel	Filterglass
Light Transmission	53%
Phosphor	Aluminised P4 Sulphide
Fluorescence	White
Phosphorescence	White
Focusing Method	Electrostatic
Deflection Method	Magnetic
Deflection Angles (approx.):	
Diagonal	110°
Horizontal	99°
Vertical	82°

Tube Dimensions:			
Overall Length	9.250	+0.125 —0.250	inches
Greatest Width	9.750	±0.100	inches
Greatest Height	8.000	±0.100	inches
Diagonal	10.875	±0.100	inches
Neck Length	4.590	±0.125	inches

Screen Dimensions (min.):	
Horizontal	9.000 inches
Vertical	7.125 inches
Diagonal	10.187 inches
Area	60 sq. in.
Electron Gun	Unipotential
Bulb	Jedec J87-A1
Bulb Contact	Jedec J1-21
Base	Jedec B7-183

SOCKET CONNECTIONS

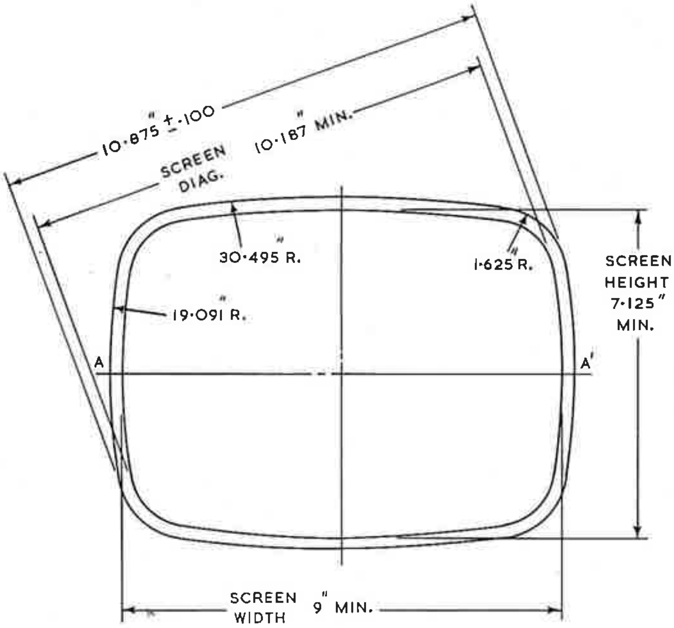
Pin 1—Heater
Pin 2—Grid No. 1
Pin 3—Grid No. 2
Pin 4—Grid No. 4
Pin 5—Blank
Pin 6—Grid No. 1
Pin 7—Cathode
Pin 8—Heater
Bulb Contact—Anode

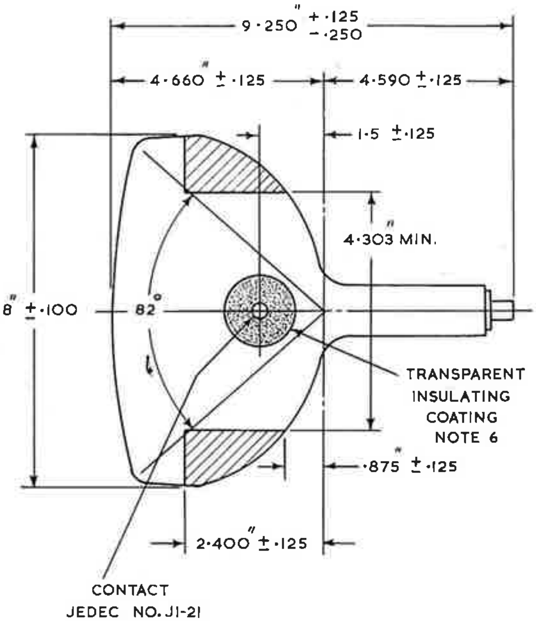


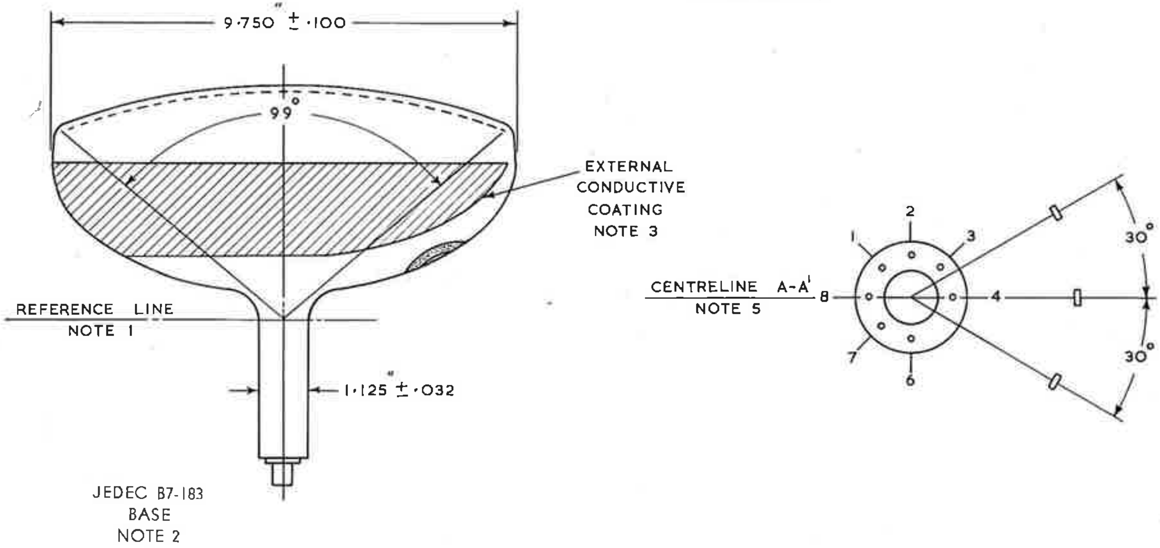
RATINGS, DESIGN MAXIMUM SYSTEM

(Unless otherwise specified, voltage values are positive, and measured with respect to cathode)

Maximum Anode Voltage	15,000 volts
Minimum Anode Voltage	9,000 volts
Maximum Grid No. 4 Voltage	+1100, —500 volts
Maximum Grid No. 2 Voltage	550 volts
Minimum Grid No. 2 Voltage	200 volts
Grid No. 1 Voltage:	
Maximum Negative Value	—154 volts
Maximum Negative Peak Value	200 volts
Maximum Positive Value	0 volts
Maximum Positive Peak Value	2 volts







Heater Voltage:	
Maximum	6.93 volts
Minimum	5.67 volts
Heater Current at 6.3 Volts	0.3 amp
Maximum Heater-Cathode Voltage, Heater Negative with respect to Cathode:	
During Warm-up, 15 secs	450 volts
After Warm-up Period	200 volts
Maximum Heater-Cathode Voltage, Heater Positive with respect to Cathode	200 volts

TYPICAL OPERATION, GRID DRIVE SERVICE

(Unless otherwise specified, all voltage values are positive with respect to cathode)

Anode Voltage	10,000 volts dc
Grid No. 4 Voltage*	0-400 volts dc
Grid No. 2 Voltage	400 volts dc
Grid No. 1 Voltage	—36 to —94 volts dc

TYPICAL OPERATION, CATHODE DRIVE SERVICE

(Unless otherwise specified, all voltage values are positive with respect to Grid No. 1)

Anode Voltage	10,000 volts dc
Grid No. 4 Voltage*	0-400 volts dc
Grid No. 2 Voltage	400 volts dc
Cathode Voltage	36 to 78 volts dc

MAXIMUM CIRCUIT VALUE

Grid No. 1 Circuit Resistance	1.5 megohms

* The grid No. 4 (or grid No. 4 to grid No. 1) voltage required for optimum focus of any individual tube will be a value between 0 and 400 volts independent of anode current. It will remain essentially constant for values of anode (or anode to grid No. 1) voltage and grid No. 2 (or grid No. 2 to grid No. 1) voltage within the ranges shown for these items.

NOTES

NOTE 1. Yoke Reference Line is determined by plane surface of flared end of JEDEC Reference Line Gauge No. 126 when seated on funnel of tube. With minimum neck length tube, the PM centring magnet should extend no more than 2⅛″ from Yoke Reference Line.

NOTE 2. Lateral strains on the base pins must be avoided. The socket should have flexible leads permitting movement. The perimeter of the base wafer will be inside a 1¾″ diameter circle concentric with the tube axis.

NOTE 3. External conductive coating forms supplementary filter capacitor and must be grounded.

NOTE 4. Neck diameter may be a maximum of 1.168″ at the splice.

NOTE 5. Base pin No. 4 aligns with centreline A-A′ within 30° and is on the same side as anode contact J1-21.

NOTE 6. To clean this area, wipe only with a soft, dry lintless cloth.

SPEED CONTROL OF SERIES MOTORS WITH SCR's

By: J. V. Yonushka

Introduction

This article describes the applications of the 2N3228 silicon controlled rectifier to speed-control circuits for fractional horse-power, series-wound (Universal) motors used in hand tools and small appliances.

Silicon controlled rectifiers have been widely accepted for power control applications in industrial systems where high performance requirements justified the economics of the application. Historically however, in the commercial high-volume market, economic considerations precluded the use of SCR's. The development of the 2N3228, rated for 117-volt line operation has changed this situation.* The 2N3228 has been specifically designed for mass production economy and offers the inherent advantages of solid-state reliability and efficiency.

The control circuits presented herein are typical of the many possible circuits applicable for series motor speed control. Each circuit has been selected to compare performance against component cost. A general description and the typical characteristics of series motors are given. Speed-control using phase angle variation is discussed and schematic diagrams of both half-wave and full-wave applications (with and without feedback) are described. The advantages and limitations of each circuit are contrasted. A method for rating and mounting the 2N3228 versus a given motor horse power rating is formulated in the last section.

General Information

Most fractional horse power motors (1/2 hp or less) are series wound as shown in figure 1. The field winding, constructed so it surrounds the armature physically, is in series with the armature and external circuit. Current flowing through the field winding produces a magnetic field which cuts across the armature conductors. The opposing field set up in the conductors by armature current subjects the individual conductors to a lateral thrust which produces armature rotation.

The ac operation of the series motor is achieved by the nature of its electrical connections. Since the ac source voltage reverses every half-cycle, the magnetic field produced by the field winding reverses its direction in conjunction with the applied ac voltage. Because the armature windings are in series with the field windings, the current through the armature windings also reverses. With both the magnetic field and armature current reversed, the lateral thrust on the armature windings remains in the same direction.

As the armature rotates through the magnetic field, a voltage counter to the impressed voltage is induced in the individual armature conductors. In halfwave operation, during the non-conducting

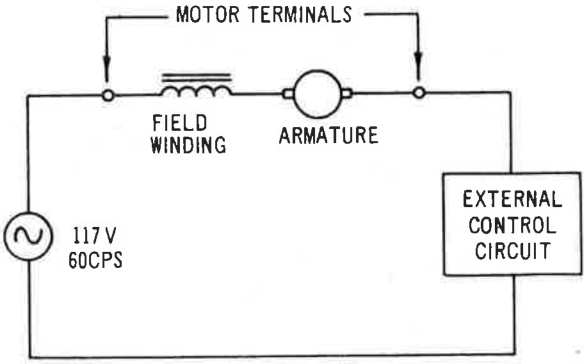


Fig. 1—Series Motor.

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* Whilst this article, which is of USA origin, refers to the 117-volt line voltage, SCR's suitable for 240-volt line operation are now becoming available.—Editor.

half cycle, the rotating armature still produces a counter emf due to the residual magnetism of the field poles. Counter emf produced in the armature conductors is therefore proportional to the armature speed.

The net current flowing through an operating motor armature depends upon the difference between the impressed voltage (emf) and the counter emf. When a motor starts, it draws more current from the line since there is no counter emf present. The current is limited only by the resistance of the field winding, armature, and external circuit. The ratio between peak starting current and peak running current can be as high as 10:1.

Theoretically, a series motor running with no load would run faster and faster until it destroyed itself. This is because the speed is inversely proportional to the magnetic flux set up by the field winding while the counter emf is directly proportional to the motor speed. Therefore, with no load, the increased speed results in a decreased magnetic flux because of increased counter emf. Actually, portable hand tools offer enough friction and armature losses to limit the no-load speeds to a safe value.

The torque of a series motor is directly proportional to the magnetic field flux and armature current. The speed of a series motor automatically adjusts itself to such a value that the difference between the impressed voltage and the counter emf permits enough current to flow to develop the torque required by the load. If the load on a motor is increased, the power to the motor must increase, requiring more current to be supplied for a constantly impressed voltage. The current can only increase if the counter emf decreases. Therefore, the speed of a series motor will decrease with increased mechanical load. Typical characteristic curves for a series motor are shown in Figure 2.

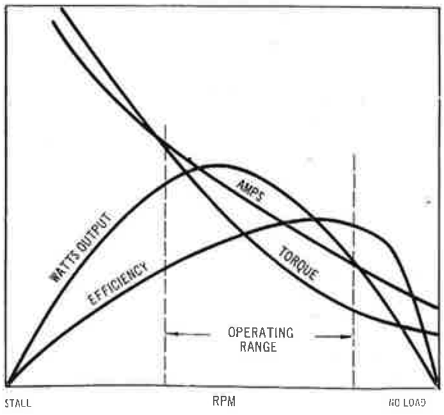

Fig. 2—Typical performance curves of Series Motors.

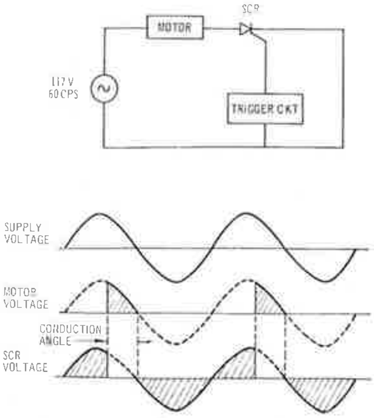

Fig. 3—Voltage shapes in AC phase control circuits.

SPEED CONTROL

One of the simplest and most efficient means of varying the power delivered to a series motor is by controlling the conduction angle of an SCR placed in series with the motor. This phase control technique is illustrated in Figure 3. Since the SCR is a rectifying device, only that portion of the cycle positive at the anode of the SCR at the time of firing is applied to the load. The SCR turns off when the supply line voltage reverses every half-cycle. Using an SCR as a half-wave rectifying device is quite convenient for variable speed control of series motors because of the dc characteristics of the motor. A typical curve showing the variation of motor speed with conduction angle of the SCR for half-wave operation is shown in Figure 4.

The speed of a series motor will adjust itself at a stable operating point to develop the torque required by the load. If more power is supplied to the motor by increasing the conduction angle, the speed of the motor will increase since the mechanical load remains the same. If the load on the motor is increased, the speed of the motor will decrease. This decrease in speed lowers the

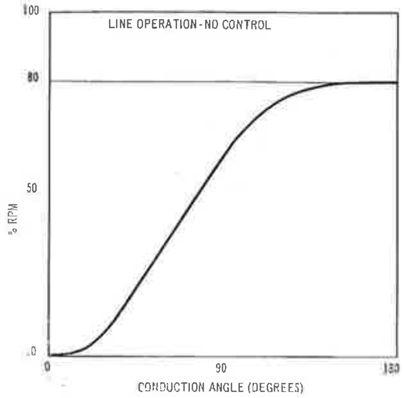

Fig. 4—Typical performance curve of series motor with half-wave phase angle control.

counter emf, allowing more current to flow to produce the increased torque required. If a constant speed is desired, the increased torque can be provided by using a greater portion of the cycle, while the speed remains the same.

APPLICATIONS

Half-Wave

The circuit of Figure 5 is recommended for applications requiring stable operation at low speeds with fixed loads. This circuit takes advantage of the phase shifting characteristics of an RC network to reduce the conduction angle beyond the peak of the applied voltage. Thus, very slow speeds are obtained for small conduction angles.

On the positive half-cycle of the applied voltage, capacitor Cl is charged through resistor R1, R2 and CRl. When the voltage on Cl exceeds the gate firing voltage of SCR1, the SCR will turn on, applying the remaining portion of the half-cycle to the load. On the negative half-cycle, Cl discharges to zero volts through R1, R2 and R3. The delay in firing SCR1 depends upon the time constant network (R1 + R2, C1,) which produces a phase shifted gate firing voltage relative to the supply voltage. The amount of phase shift is adjusted by R1. With maximum resistance in the circuit, the RC time constant is longest. This results in a large phase shift with a correspondingly small conduction angle and slow motor speeds. With minimum resistance, the phase shift is small with essentially full line voltage applied to the load, giving maximum speed. It should be noted that this circuit does not provide torque compensation, therefore, care should be exercised to prevent stalling of the motor. Under stall conditions, currents can become excessive. Subjecting the SCR to a stall current greater than 1 second may result in damage to the SCR pellet.

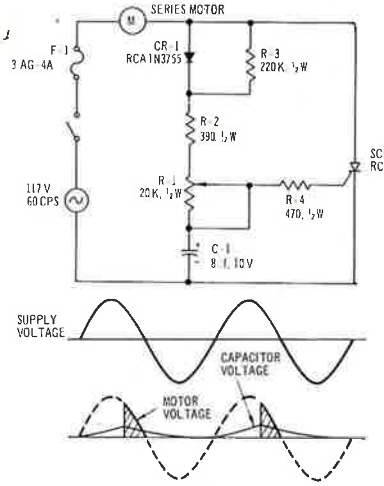

Fig. 5—Half-wave motor control, no regulation.

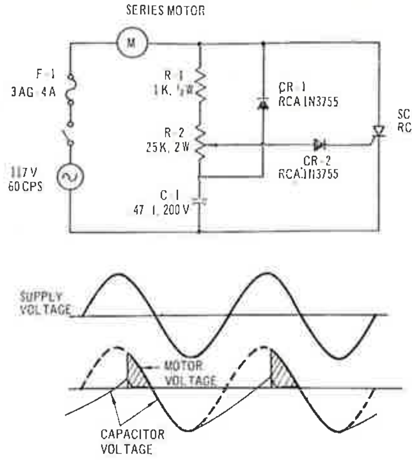

Fig. 6—Half-wave motor control, no regulation.

Another, and more accurate type of motor control is shown in Figure 6. This circuit uses the same phase shifting technique as explained in Figure 5. However, on the negative half-cycle, capacitor C1 charges to the full peak negative potential through CR1. When the negative potential starts decreasing, CR1 becomes reverse biased and C1 discharges to a positive potential through R1 and R2. As the voltage on C1 becomes positive SCR1 will fire at a conduction angle dependent upon the time constant network of (R1, R2, C1). Diode CR2 protects the gate-cathode junction from large reverse voltages. Since C1 must discharge from a high negative potential, the slope of the discharge curve is greater. This results in more uniform firing of the SCR.

The circuit shown in Figure 7 reduces spread in gate turn-on characteristics. This circuit depends upon the fast switching characteristics of transistors. The phase shift characteristics are still retained to give conduction angles less than 90° through the RC network of R1, R2 and C1. Bias network R3 and R4 provides turn-on current to the base of Q1 when the voltage on C1 becomes large enough on the positive half-cycle. Base current flowing in Q1 turns Q1 on, supplying base current to Q2. When Q2 turns on it supplies more base current to Q1 providing more regeneration to saturate the transistors rapidly. Capacitor C1 discharges through the saturated transistors into the gate of the SCR since the emitter of Q1 is directly connected to the gate of the SCR. When the SCR fires, the remaining portion of the positive half-cycle is applied to the motor. Speed control is accomplished by changing the setting of R1. With the values shown in Figure 7, the threshold voltage for firing the circuit is approximately 8-volts.

The control circuit shown in Figure 8 uses the breakdown voltage of a neon lamp as a threshold setting for firing the SCR. The NE-83 neon lamp is specifically designed for and is capable of

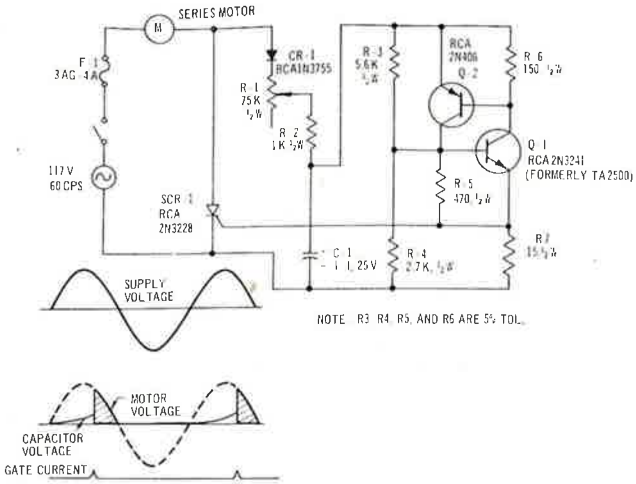

Fig. 7—Half-wave motor control, no regulation.

handling the high current pulses required for triggering SCR's. When the voltage on C1 reaches the breakdown voltage of the neon lamp, the lamp fires and C1 discharges through the lamp to its maintaining voltage. At this point, the lamp again reverts to its high impedance state. The discharge of the capacitor from breakdown to maintaining voltage of the neon lamp provides a current pulse of sufficient magnitude to fire the SCR. Once the SCR has fired, the voltage across the phase shifting network reduces to the forward voltage drop of the SCR for the remainder of the half-cycle. The capacitor discharges through CR2 and R3 from the maintaining voltage of the neon lamp to the forward voltage drop of the SCR. On the negative half-cycle, the capacitor charges to approximately -20 volts. The higher breakdown voltage of the neon lamp reduces slightly the range of conduction angles. The range of conduction angles of the circuit of Figure 8 is approximately 30° to 150°. The high breakdown voltage of the neon lamp provides excellent noise rejection and prevents erratic firing of the SCR due to brush noises on the voltage supply lines.

A fundamental circuit which is quite effective in providing motor speed control for series type motors is shown in Figure 9. This circuit makes use of the counter emf induced into the rotating armature due to residual magnetism on the half-cycle when the SCR is blocking. Because the counter emf is a function of speed, it is used as an indication of speed changes for mechanical load variations. The gate firing circuit is a resistance network consisting of R1 and R2. During the positive half-cycle of the source voltage, a fraction of the voltage is developed at the centre tap of the potentiometer and compared with the counter emf developed in the rotating armature of the motor. When the bias developed at the gate of the SCR from the potentiometer exceeds the counter emf of the motor, the SCR fires, applying potential to the motor for the remaining portion of the positive half-cycle. Speed control is accomplished by varying the potentiometer setting from maximum to minimum. If the SCR is fired early in the cycle, the motor operates at high speed since essentially, rated line voltage is applied to the motor. If the SCR is fired later in the cycle, reduced average voltage is applied to the motor with a corresponding reduction in motor speed. On the negative half-cycle, the SCR blocks voltage to the motor. Since the voltage applied to the gate of the SCR is a sinewave and in phase with the supply voltage, the minimum conduction angle occure at the peak of the sine wave and is restricted to 90°. increasing conduction angles occur when the gate bias to the SCR is increased to allow firing at voltage values less than the peak value of the voltage at the centre tap of the potentiometer.

At no load and low speed, skip cycling operation occurs. This results in erratic motor speeds. Since no counter emf is induced in the armature when the motor is standing still, the SCR will fire at low bias settings (potentiometer) causing the motor to accelerate to a point where the counter emf induced in the rotating armature exceeds the gate firing bias of the SCR and prevents the SCR from firing. The SCR is not able to fire again until the speed of the motor has reduced due to friction losses, to a value where the induced voltage in the rotating armature is less than the gate bias. At this time the SCR fires again. Because the motor deceleration occurs over a number of cycles, there is no voltage applied to the motor hence, the term skip cycling.

When a load is applied to the motor, its speed decreases thereby reducing the counter emf induced in the rotating armature. With a reduced counter emf, the SCR fires earlier in the cycle, providing increased motor torque to the load.

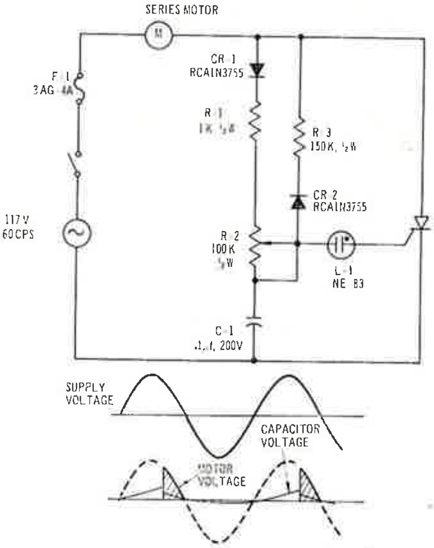

Fig. 8—Half-wave motor control, no regulation.

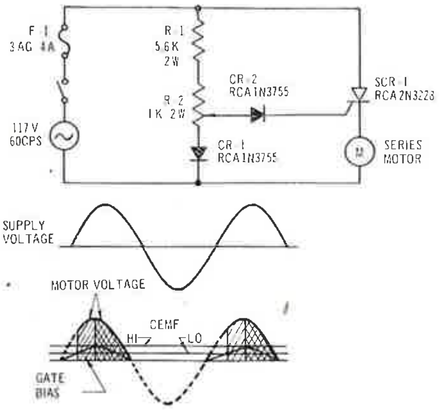

*Fig. 9—Half-wave Motor control, with regulation**

Figure 9 also shows variations of conduction angle with changes in counter emf. The counter emf appears as a constant voltage at the motor terminals when the SCR is blocking. Since the counter emf is essentially a characteristic of the motor, this may vary between various motors, requiring other potentiometer settings for comparable operating conditions of different motors.

Figure 10 shows a variation of the Figure 7 circuit. The basic difference between the two circuits is that Figure 10 circuit provides feedback for changing load to maintain essentially a constant speed. The feedback is provided by R7 which is in series with the motor. A voltage proportional to the peak current through the motor, is developed across this resistor. This voltage is stored on capacitor C2 through diode CR2 and is of such polarity to change the bias on the resistance network of R3 and R4 in accordance with the load on the motor. With an increasing motor load, the speed tends to decrease. This causes more current to flow through the motor armature and field.

With increasing current flowing through R7, the voltage scored on capacitor C2 increases in the positive direction. This causes the transistors to conduct earlier in the cycle to fire the SCR and provide a greater portion of the cycle to the motor. With a decreasing load, the motor current decreases, reducing the voltage stored on C2. This causes the transistors and SCR to conduct later in the cycle, reducing the average power supplied to the motor and resulting in a reduced torque for the smaller load. The advantage of this circuit is that a wide range of stable speeds can be obtained without any rewiring of the motor. Since the motor current is a function of the motor itself, resistor R7 has to be matched with the motor rating to provide the necessary feedback for proper load compensation. Resistor R7 may range in value from 0.1 ohm for larger size motors to 1 ohm for the smaller motors.

Full Wave

A full-wave motor control circuit with SCR's back-to-back is shown in figure 11. The circuit is essentially the same as that shown in Figure 6. SCR1 conducts during the positive half-cycle at a conduction angle determined by the setting of R2. SCR2 conducts during the negative half-cycle. Both SCR's conduct for approximately the same conduction angle on opposite half-cycles. This is because potentiometers R2 and R3 are ganged together. Since this circuit does not provide regulation for load variations, it should only be used on fixed loads which will not stall the motor under any operating condition.

The circuit shown in Figure 12 provides full-cycle control with only one SCR. The bridge rectifier is used to provide full-wave rectified voltage to the SCR and its control circuitry while applying both half-cycles to the series motor. The duty cycle on the SCR in this configuration is greater than that for half-wave operations, therefore the load considerations given in the Ratings and Limitations section of this article should be observed. The phase shifting properties of an RC network are used to provide conduction angles less than 90°. However, skip cycle operation for this circuit is more severe than for the half-wave case. Because of this, minimum conduction angle should be 60°. This is the minimum at which stable operation occurs. Operating at this conduction angle will result in a speed reduction of approximately half of full-cycle speed. The circuit description for this configuration is basically the same as that of Figure 5 with the exception of full-cycle conduction.

A full-cycle equivalent of the half-wave circuit using the two-transistor circuit for fast "turn-on" (Fig. 7) is shown in Figure 13. This circuit also uses a full-wave bridge for reducing the number of components for full-cycle operation.

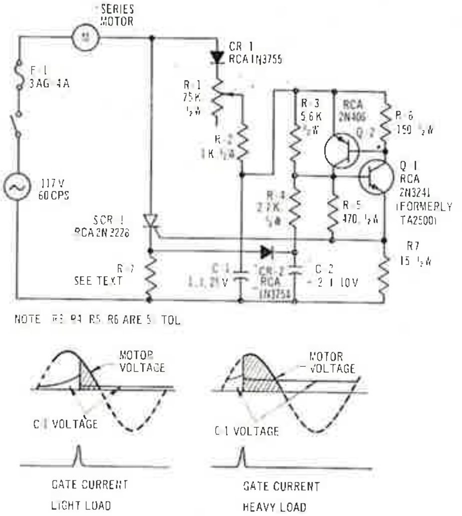

Fig. 10—Half-wave motor control, with regulation.

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* Circuit concept originally proposed by James W. Momberg.

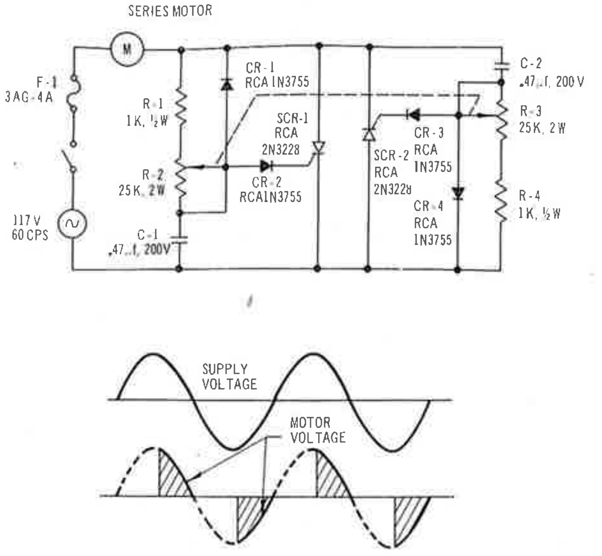

Fig. 11—Full wave motor control, no regulation.

A modified version of Figure 13, designed for applications requiring feedback for compensation of load changes, is shown in Figure 14. Operation is the same as that described for Figure 10 with the exception of full-cycle conduction. In this circuit, R7 should be matched to the characteristics of the specific motor application. The resistor will vary in range from .1 to 1 ohm.

RATINGS AND LIMITATIONS

Since semiconductors, like many other electrical devices, are limited in their power dissipation abilities because of package size and environment, ratings are usually given for a particular heat sink size at a prescribed ambient or case temperature. In applications such as described in this article, high in-rush and stall currents must be considered. Maximum motor size should be limited to a nameplate rating up to 3 amperes rms. For fractional horse power motors with nameplate data given in developed horse power to the load, the mechanical power must be converted to electrical power. Internal losses of the motor must also be considered when determining input power. A figure of merit to use is 50 per cent efficiency for fractional horse power motors, indicating that the power input to the motor is twice the power delivered to the load. Using the figure of merit of 0.5 and 115 volt input voltage, the rms current to the motor can be calculated using:

$$\text{RMS Current} = \frac{\text{Horse Power} \times 746}{115 \text{ Volts} \times .5}$$

$$= \text{Horse Power} \times 13$$

(The current calculated from this formula should not exceed 3 amperes maximum for the motor applications in this article.)

The current rating is also based upon the SCR being mounted on an aluminium heat sink having an equivalent dimension of 3″ x 3″ x 1/16″. The heat sink may be a single plate on which the SCR is mounted, or advantage may be taken of housing or packaging availability by electrically insulating the SCR from the heat sink with a mica washer. The use of silicone grease between metal and mica will provide a better thermal contact for more efficient heat dissipation. In critical areas, a combination of fin and frame may be used to secure the necessary heat sink area for reliable operation. The ambient temperature in the vicinity of the semiconductor should be limited to a maximum of 50°C (122°F) when operating at full rated current of the circuit. For applications requiring higher temperatures, reliable operation can be obtained through the use of cooling air across the heat sink.

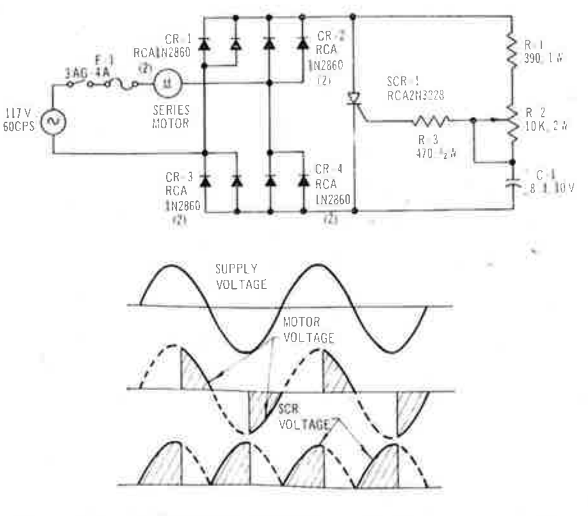

Fig. 12—Full-wave motor control, no regulation.

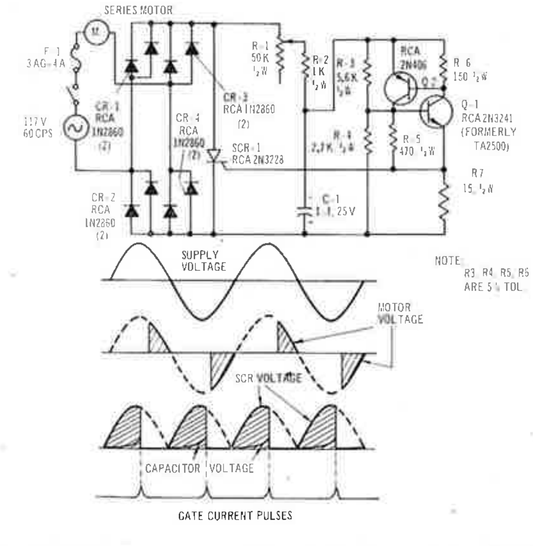

Fig. 13—Full-wave motor control, no regulation.

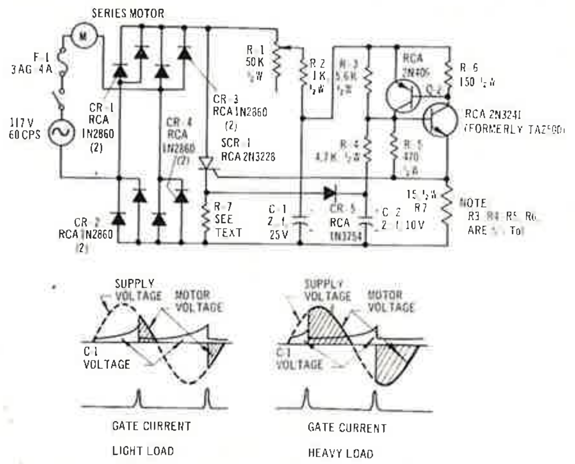

Fig. 14—Full-wave motor control with feedback.

It must be emphasised that operation of the series motor at low speeds and heavy mechanical loads may produce large currents and tend to stall the motor. Under such conditions, operation should be limited to less than a second to prevent blowing of the fuse or possible damage to the SCR. Fuse ratings should be carefully observed and limited to the values indicated.

The emphasis for these circuits is on simplicity and economy. A higher degree of speed regulation can be achieved by more complex firing and feedback circuits. Pulsed gate signals and feedback gain can provide improved speed regulation and stability and minimise temperature effects on the firing characteristics of the SCR.

CONCLUSIONS

In the operation of series motors under normal use, the versatility of speed control provides many different applications for the user. Several methods of speed control were presented in this article. The performance of these circuits will be adequate for a large number of motor applications. Depending upon the individual needs of the user, either half-wave or full-wave, with or without feedback, can be selected. A convenient method of speed control is to use the half-wave circuits for variable speeds and shunt the SCR and its control circuitry with a switch for full power operation.

ACKNOWLEDGEMENT: The author wishes to thank the many RCA customers and friends who have so willingly contributed to the concepts and circuits for this note. Transistor circuit configuration for SCR firing proposed by G. Hanchett.

NOTE: All of these circuits have been developed for 117 volt line operation with the 2N3228. For 230 volt line operated motors a specially rated higher voltage device (RCA 40230 SCR) is available. Circuits would have to be redesigned accordingly.

(With acknowledgements to RCA.)

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