The Development of Electron Tubes for a New Coaxial Transmission System

By G. T. FORD and E. J. WALSH

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1. Introduction

As THE demand for long distance telephone circuits has increased, new transmission systems capable of handling more channels per conductor have been developed. Also the advent of television has created a demand for broad band channels for network facilities. One of the latest developments now nearing completion is the L3 Coaxial System.

Three new tubes have been developed specifically to meet the exacting requirements of this system: two tetrodes, the W.E. 435A and W.E. 436A, and a triode, the W.E. 437A. All three types are used in the line and office amplifiers. The new tubes make possible a substantially higher level of broad band amplifier performance compared to their predecessors. They represent the result of improvements made by applying well known basic principles through new tube-making techniques. These techniques have been developed largely within the framework of existing conventional telephone tube manufacturing methods.

The development of special, small, low power vacuum tubes for high frequency application in the Bell System began in 1934. The tube program was instituted originally as part of a research project in the field of radio communications. When the development of the L1 Coaxial System began it was recognized that similar tubes would be needed. Part of the tube development effort was therefore directed toward the coaxial requirements. Work on the W.E. 384A and W.E. 386A tubes used in the L1 system was completed in 1939 as an outgrowth of this program.

The demand for amplification over wider frequency bands resulted in further development work along the same lines. During World War II this effort was applied to the development of the 6AK5 tube which became available early in 1943 and was used widely in IF amplifiers in radar equipment. Shortly after the war the W.E. 408A tube was developed for telephone repeater uses. This is a long life version of the 6AK5 tube having the same electrical characteristics except for the heater voltage and current. The W.E. 404A tube appeared in telephone circuits in 1949. This tube, having a higher figure of merit than the W.E. 408A, provided improved performance in the IF amplifiers used in the New York to Boston radio relay system and in the TD2 radio relay system. The W.E. 435A, W.E. 436A and W.E. 437A tubes are the latest types to come out of this long range program.

It will be seen in what follows that the key to continued development along these lines has been improvements in the techniques of grid making to meet the basic objective of providing a grid which can be spaced very close to the cathode and which, in effect, acts as a uniform potential plane controlling the current drawn from the cathode without offering any physical obstruction. This objective is approached by using many turns of very small diameter wire for the grid winding. The reason for the close grid-cathode spacing is that the transconductance or sensitivity depends on this factor. Although the increase in input capacitance which results is a disadvantage because of its effects on the interstage circuits, this disadvantage is more than compensated for by the higher transconductance obtained.

2. Principles of Design

2.1 *Requirements*

The overall requirements for the L3 system, and the manner in which they are related to the tube parameters, are very complex. However, in its simplest terms, the objective for the L3 system is to provide on one coaxial p pe a facility suitable for the simultaneous transmission over a 4000-mile circuit of a television signal and 600 one-way telephone channels or, alternatively, 1800 one-way telephone channels when no television channel is required. The transmission band being provided is from approximately 0.3 MC to approximately 8 MC. The amplifier needed to compensate for the cable attenuation must meet very exacting requirements with respect to gain-frequency characteristics, stability, noise, and linearity.

The design features necessary to provide suitable electron tubes for use in the L3 amplifiers are closely related to the requirements mentioned above for the amplifiers. In general terms, the tube design objectives are: (1) high transconductance-capacitance ratio (figure of merit), (2) minimum excess phase shift or phase delay, (3) low noise, (4) well controlled modulation, (5) long life, (6) interchangeability, and (7) lowest cost consistent with the first six objectives. In the material which follows, each of these objectives will be discussed in detail and its relationship to the system objectives brought out.

2.2 *Figure of Merit*

Figure of merit is of particular importance. It is a direct measure of the bandwidth over which the required amplification can be obtained. In general, a given factor of improvement in the figure of merit can be translated directly into a wider transmission band providing more communication channels.

For a two-terminal type of interstage such as that used in the L3 amplifier, the figure of merit is

$$F = GB = \frac{KG_m}{2\pi(C_1 + C_2)} \tag{1}$$

where F is the figure of merit, G is the voltage amplification, B is the bandwidth between the frequencies where the gain is 3 db below that at the center frequency, K is a constant whose value depends on the particular interstage design, G_m is the transconductance of the tube, C_1 is the input

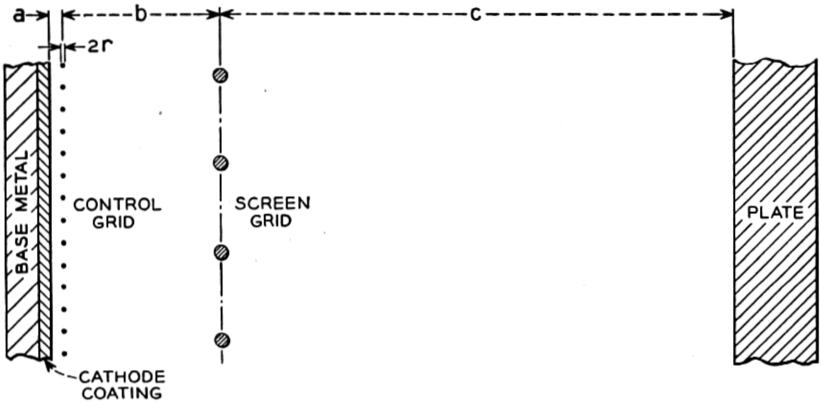

Fig. 1—Geometry of the 436A tube.

capacitance, and C_2 is the output capacitance. This figure of merit is directly applicable to a tetrode operated as a small-signal voltage amplifier and is a well known relationship.[1] It will be used to show how the tube design factors influence the figure of merit of the W.E. 435A and W.E. 436A tubes.

Using equation (1) and applying certain simplifying assumptions which can be made without materially affecting the results, expressions are derived in the appendix showing the relationship between the figure of merit and the tube parameters. Equations (2) and (4) in the appendix show how the figure of merit is affected by the grid-cathode spacing "a", the grid-screen spacing "b", the screen-plate spacing "c", and the grid wire radius "r". See Fig. 1. Equation 3 gives the required screen voltage for the as-

[1] "Characteristics of Vacuum Tubes for Radar Intermediate Frequency Amplifiers," G. T. Ford, *B.S.T.J.*, Vol. XXV, p. 389, July, 1946.

sumed current density and geometry. Since these expressions are rather involved, the manner in which the various factors influence the figure of merit can be brought out best by a series of curves. Figures 2, 3, and 4 show how F is affected by changes in "a", "b", and "c". Figures 6 and 7 show how the screen voltage required to get the assumed current density with a given bias E_{c1} varies with "a" and "b" (equation 3). The screen voltage is essentially independent of "c".

These relationships are also applicable to the W.E. 437A tube with minor modifications.

2.21 *Design Considerations*

How the various factors in equations (2), (3), and (4) affect the figure of merit will be discussed in detail. They are listed in Table I.

The factor M is the ratio of the plate current to the cathode current. The figure of merit is directly proportional to this factor. M can be increased

TABLE I

Factor	Design Values	Practical Design Considerations
M	0.75	Mechanical, plate-grid capacitance
I_0	50 MA/cm²	Stability of emission, life
a	0.00635 cm	Mechanical
b	0.0444 cm	Screen voltage, mechanical
c	0.150 cm	Formation of potential min.
r	0.00038 cm	Mechanical
E_{c1}	−1.5 volts	Grid current
E_{c2}	150 volts	Dissipation, life

by using smaller wire in the screen grid, the minimum practical wire size being determined by the mechanical rigidity and heat dissipation capability required. M can also be increased by reducing the number of turns on the screen, but this is limited by the necessity for sufficient shielding effect to meet the requirement that the plate-grid capacitance be less than a specified value.

Since the figure of merit is directly proportional to the cube root of the cathode current density I_0, the improvement with increasing I_0 is not very rapid. The problems of obtaining uniform initial performance and long life are aggravated by increasing the current density, for several reasons. There is no direct evidence to show that high current density per se causes accelerated loss of available emission. In fact there is some evidence to the contrary.[2] However, there is ample evidence that phenomena

[2] "Influence of Density of Emission on the Life of Oxide Cathodes," S. Wagener, *Nature*, p. 357, Aug. 27, 1949.

usually associated with high current density tend to shorten the life. Higher electrode temperatures, higher potentials, and the production of more ions are the major items in this category. It is presumed that the shorter life found under these conditions is due to the greater rate of contamination of the cathode by material from the other parts of the tube. Great efforts have been made to find and to use processing techniques which will minimize this kind of limitation and to introduce constituents into the cathode which will counteract such deterioration. The situation at the time the L3

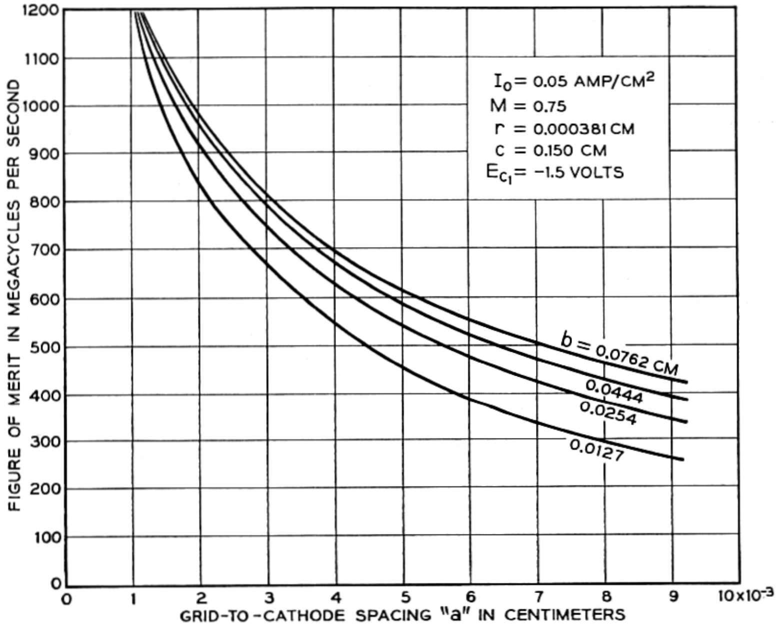

Fig. 2—Figure-of-merit vs. grid-to-cathode spacing.

tubes were being developed was that 50 MA/cm^2 was as high a current density as seemed to be consistent with the long life required.

It is apparent from the curves in Fig. 2 that the figure of merit increases rapidly as the grid-cathode spacing "*a*" is reduced. The limitation here is mechanical and manifests itself in two ways. One is the practical difficulty of spacing the parts so closely with sufficient accuracy. The other is the problems associated with fabricating grids wound with wire of small enough diameter to make effective use of the close grid-cathode spacing. This part of the subject will be discussed in detail later. It is one of the most important aspects of the design of the L3 tubes.

It would appear from Fig. 3 that the grid-screen spacing "b" should be as large as possible. However, the required screen voltage increases as "b" increases, and it is desirable to keep the screen voltage low. Therefore, "b" is made as low as possible without causing too much penalty on figure of merit. A good compromise value for "b" depends on the range of grid-cathode spacing "a" being considered, but it will usually be from 0.005 cm to 0.020 cm for close spaced tubes.

Figure 4 shows that the figure of merit increases as "c" increases, but there is very little advantage in making it more than 0.040–0.050 cm. Making it much larger also increases the outside dimensions of the structure unnecessarily, and eventually leads to a spacing which will cause irregularities in the plate current-plate voltage characteristic due to space charge effects in the screen-plate space.

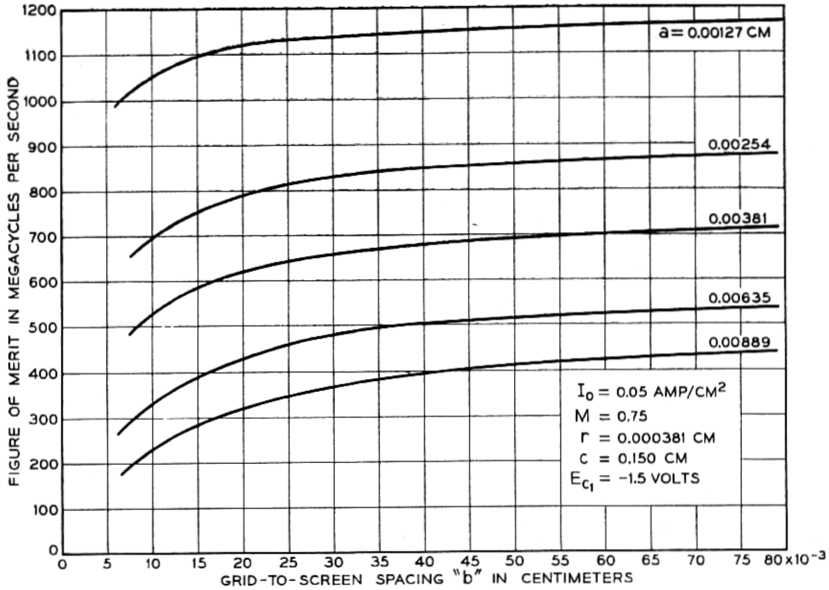

Fig. 3—Figure-of-merit vs. grid-to-screen spacing.

Although it is not apparent from the curves or from what has been said above, it is desirable to have "r" as small as possible. It is obvious that "r" must be less than $\frac{1}{2n}$, otherwise the grid is completely closed. Under the assumption that $na = 1$, this means that "r" must be less than $0.5a$ if there is to be open space between the grid wires. Actually, it is desirable to have not more than 30% of the projected area of the grid closed, which means that "r" should be less than $0.15a$. In addition to this consideration, it is desirable to have "r" considerably less than $0.15a$ so that the required screen voltage will be as low as possible. This comes about because the amplification factor μ increases as "r" is increased, other quantities held constant, and equation (3) shows that E_{c2} increases as μ increases. The diagram shown in Fig. 5 illustrates the trend in grid-cathode spacings and grid wire sizes. The W.E. 416A tube (formerly BTL 1553) represents the

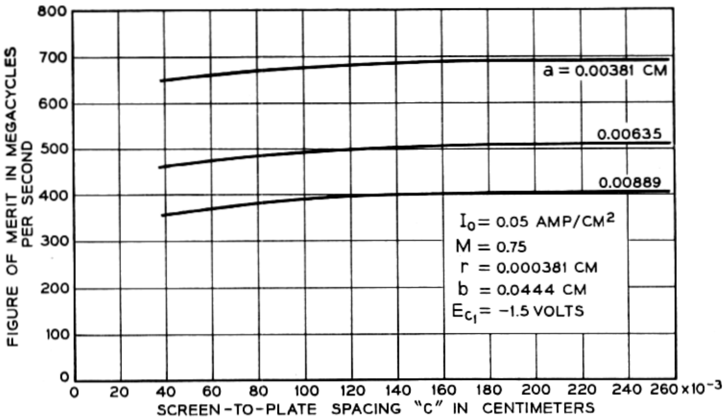

Fig. 4—Figure-of-merit vs. screen-to-plate spacing.

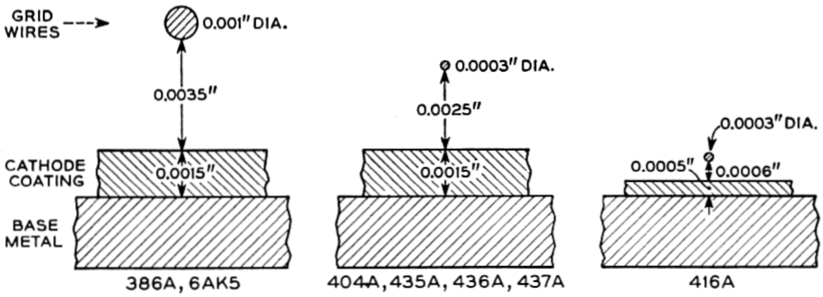

Fig. 5—Trend in spacing and grid wire size.

greatest extension of this trend reported as far as grid-cathode spacing is concerned.[3]

The figure of merit increases as the absolute value of the bias E_{c1} is reduced, since I_0 increases. However, a minimum bias value of about −1.5 volts is usually necessary in order to avoid undesirable effects due to the

[3] "Design Factors of the Bell Telephone Laboratories 1553 Triode," J. A. Morton and R. M. Ryder, *B.S.T.J.*, Oct. 1950.

collection of electrons of high initial velocity by the control grid. Such grid currents contribute to the noise, cause input loading, and may also cause excessive signal distortion.

Since I_0 increases as the screen voltage E_{c2} is increased, the figure of merit likewise increases. It is desirable to keep E_{c2} as low as possible for at least three reasons. The most important is that high screen voltage will generally have an adverse effect on tube life. The second is that low power consumption is desirable for economic reasons and the third is that it helps from the standpoint of maintaining low temperatures of the components in an

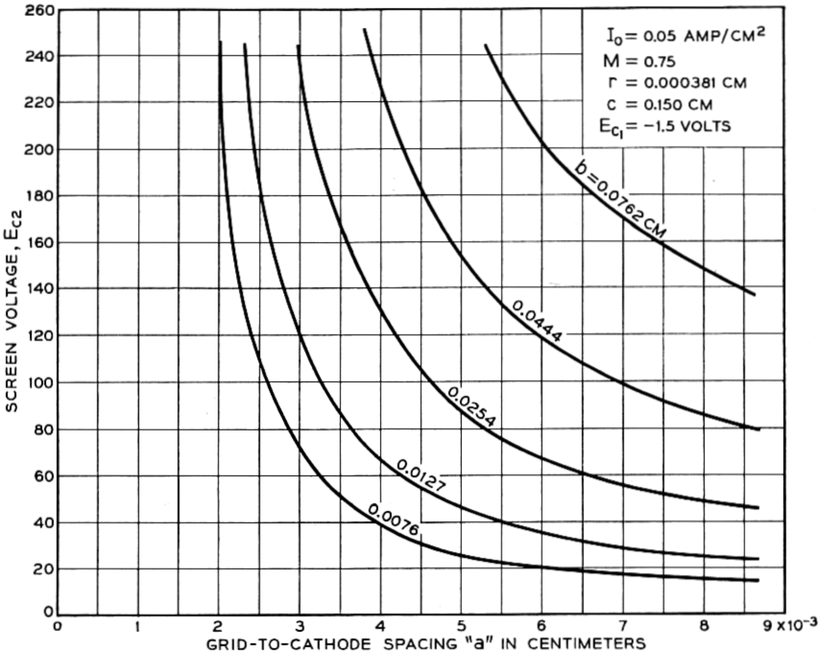

Fig. 6—Screen voltage vs. grid-to-cathode spacing.

amplifier. Figures 6 and 7 show how E_{c2} depends on "a" and "b". The requirement that E_{c2} be kept low means that the range of "a" and "b" which can be used is restricted.

2.3 *Phase Shift*

The effects of electron transit time and lead inductance in the tubes must be taken into account in order to meet the amplifier requirements with respect to phase margin. In order to maintain stable operation over the desired transmission band, the gain and phase characteristics must be controlled up to about 200 MC. The amount of phase shift at the frequency where the gain becomes unity ("cross-over point") is of particular interest. In the L3 amplifier this frequency is about 40 MC. Phase shift introduced by electron transit time and by lead inductance is referred to as "excess phase." Ideally, of course, the excess phase would be zero.

The time required for an electron to travel from the cathode to the plate is of the order of 10^{-10} seconds. This corresponds to about 5° of excess phase at 40 MC. Close spacings and high electrode potentials tend to reduce the

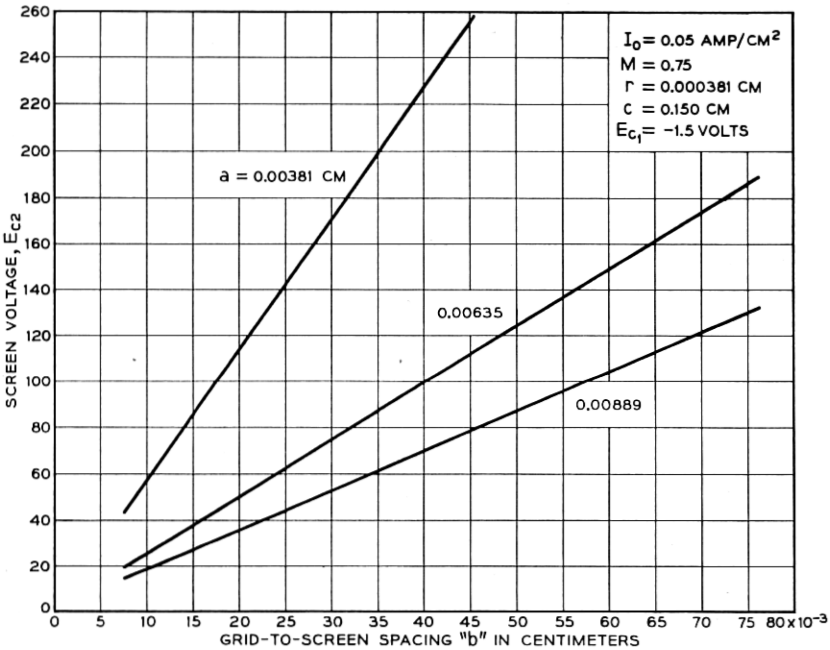

Fig. 7—Screen voltage vs. grid-to-screen spacing.

transit time. However, the considerations discussed in Section 2.2 have been the major factors in setting the spacings and potentials because the transit time, though important, is far less so than the figure of merit.

By using relatively heavy lead wires and mounting the tube structure in such a way as to make the lead wires as short as possible, the additional excess phase due to the lead wires has been minimized so that it amounts to about 5° at 40 MC.

In order to insure adequate margin against a singing condition, the amplifier has been designed to have about 20°–30° less phase shift at 40 MC with these tubes than that which will cause singing. With this situation, it can be seen that any substantial factor of increase in the excess phase introduced by the tubes, or any other components, could begin to reduce the phase margin seriously.

2.4 *Noise*

Fluctuation noise is an important factor in the W.E. 435A used in the first stage of the input amplifier and in the W.E. 436A used in the first stage of the output amplifier. There is adequate margin against the effect of low frequency noise components such as microphonics, power frequency hum, and "sputter noise" if reasonable precautions in tube and circuit design are taken. From a design standpoint, the fluctuation noise is minimized by adopting a combination of cathode temperature and current density drawn such that, with a normally active cathode, the space current is substantially space charge limited, with ample margin for some loss of cathode activity in service before the temperature limited condition is approached. When the temperature limited region is reached, the noise is substantially higher than for the space charge limited condition. The temperature and the cathode current density ratings for these tubes have been set at values which take these considerations into account.

2.5 *Modulation*

Since a major purpose of using feedback is to reduce the modulation products arising in the amplifiers, the more nearly an ideal linear transfer characteristic can be approached in the tube design the better, because less feedback is required to obtain a given grade of system performance. Unfortunately, however, a conventional triode or tetrode type of vacuum tube operating under normal space charge limited conditions necessarily has a transfer characteristic which is non-linear. Several possible special structures which might give less modulation were explored, but none were found which would provide the required figure of merit and be sufficiently stable and reproducible.

Considerable emphasis was placed on the problem of controlling the variation in modulation from tube to tube. The most important factors are grid-cathode spacing, uniformity of grid pitch, and cathode activity. Although these factors must be well controlled for other reasons also, the special requirements on modulation necessitated a thorough investigation.

The effect of the grid-cathode spacing can be expressed in terms of the d-c. plate current and the signal level. For a triode having an idealized three-halves-power transfer characteristic with $\frac{d\mu}{dE_{c1}} = 0$ as in Section 2.2, and for small signals, the ratio of the fundamental signal current to the second harmonic component for the case of a very small load impedance is

$$\frac{I_p}{I_{2p}} = 12 \frac{I_b}{I_p} \quad \text{(see appendix for derivation)} \tag{11}$$

This means that, for a given signal current amplitude I_p in the output, a tube having the assumed characteristics will give a ratio which depends only on the d-c. plate current, which in turn is very sensitive to changes in grid-cathode spacing.

A study of the variations in grid pitch and their effects on modulation in a particular experiment showed that reducing the standard deviation of the pitch distance from 16% to about 7% reduced the second-order modulation by 4 db. Since the second-order modulation must be reduced by feedback which is at a premium in the L3 system, this experiment showed that control of the grid pitch was important, and that periodic checks on this factor would be desirable in manufacture.

The effect of cathode activity on modulation was studied in diodes so as to eliminate the effects of grid variations. The variations in modulation from tube to tube were found to be about the same as when grids were present. The geometry of the diodes was so closely controlled that dimensional variations could not account for the differences in the modulation levels. This part of the investigation led to a recognition of the importance of obtaining the best possible uniformity of cathode activity. It also became apparent that the surface condition of the anode was a factor, and that it is therefore desirable to maintain a high degree of cleanliness of the electrodes to which positive potentials are applied.

2.6 *Life*

Long tube life is a very important requirement in the L3 system. The most important consideration is the effect of the life on the reliability of the system. There is also the obvious effect of the life on maintenance costs.

Short life tends to reduce the reliability of a system which contains a great number of tubes because the potential failures cannot be predicted so accurately as when the life is long, without a prohibitively costly amount of testing. Even with the most frequent and accurate testing procedure which might be considered, it would be amazing if more than 90% of the potential failures were replaced before causing transmission trouble. To illustrate the effect of short life, consider a 100-mile section of L3 line. There will be five tubes in each of 24 amplifiers. If the performance of any one of the total of 120 tubes becomes poor enough to make the circuit uncommercial, that section must be taken out of service until the defective tube (or amplifier) is replaced. Now, for a going system, with 120 tubes, and assuming an abnormally short life of say 1200 hours, a tube will fail every ten hours on the average unless preventative testing is used. Even if very frequent testing be done in order to replace 90% of the potential failures before they occur, one circuit interruption every 100 hours may be expected.

It is evident that a life many times greater than that assumed in this illustration is imperative if reliable service is to be obtained and costly maintenance avoided. Laboratory life tests predict that a tube life of at least 15,000 hours may be expected in the L3 system. The actual results will depend on the extent to which the operating conditions are closely controlled, the severity of the field rejection limits, and the ability of the tube factory to control the processing.

2.7 *Interchangeability*

The objective is to make the characteristics of the tubes sufficiently uniform so that tubes may be replaced at will without circuit adjustments being needed. In the L3 amplifiers, the circuits have been designed so that a relatively wide range of characteristics can be accepted for individual tubes. However, it is essential that the average characteristics be held in close control from one manufacturing lot to another. This has been provided for by setting up distribution requirements which will be discussed further in a later section.

2.8 *Cost*

As will be seen from the description which follows, it has been possible to meet the L3 requirements with tube designs which do not require too great departures from the manufacturing methods employed for conventional telephone tubes. With a reasonable demand, it is accordingly expected that the tube costs should be moderate.

3. Design Description and Characteristics

3.1 *Mechanical Description and Mechanical Problems*

Figure 8 shows the three L3 tubes along with some of the earlier high figure of merit tubes. The W.E. 386A (left hand side) was designed to be soldered directly into the circuits and had its input lead at the stem end while the output lead came out through the top of the bulb. The flexible leads used for soldering purposes, and the double-ended lead construction, add materially to the cost of tube construction and testing. Early in the L3 tube development the question of factory cost compared with circuit performance was weighed and it was decided that the advantage of lower tube cost plus the very large advantage of simple plug-in tubes would outweigh

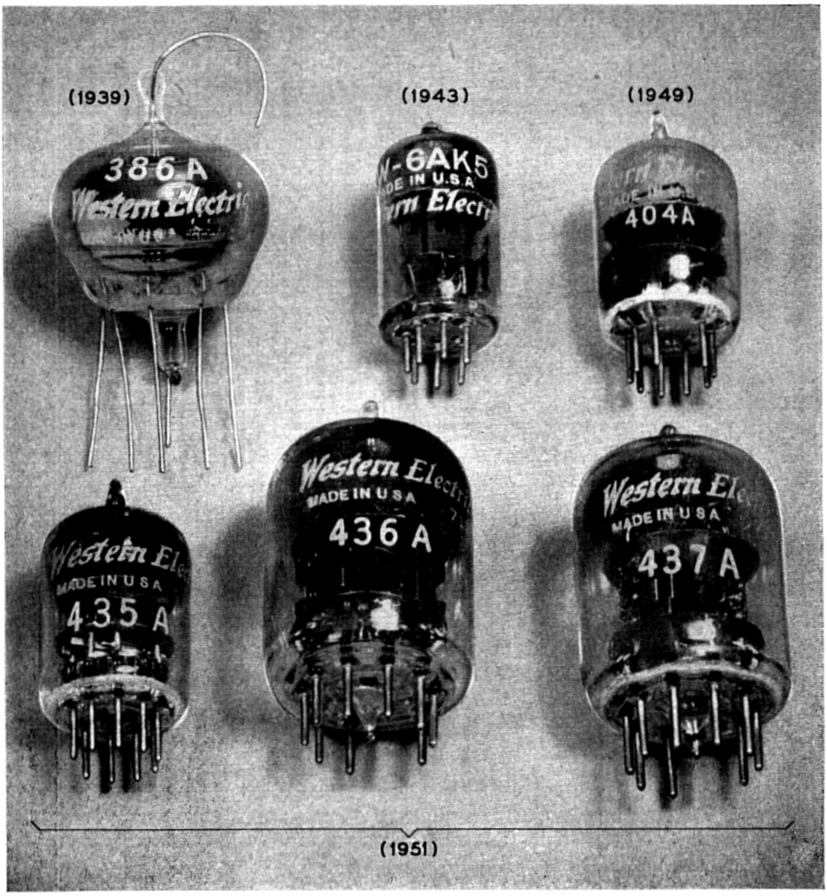

Fig. 8—The 386A, 408A, 404A, 435A, 436A and the 437A tubes approximately actual size.

the cost in performance. Accordingly, all three L3 tubes are of the stiff pin, plug-in type designed to fit existing sockets. The price paid for obtaining the advantages of lowered cost and interchangeability has been a loss in feedback of approximately 2 db per amplifier.

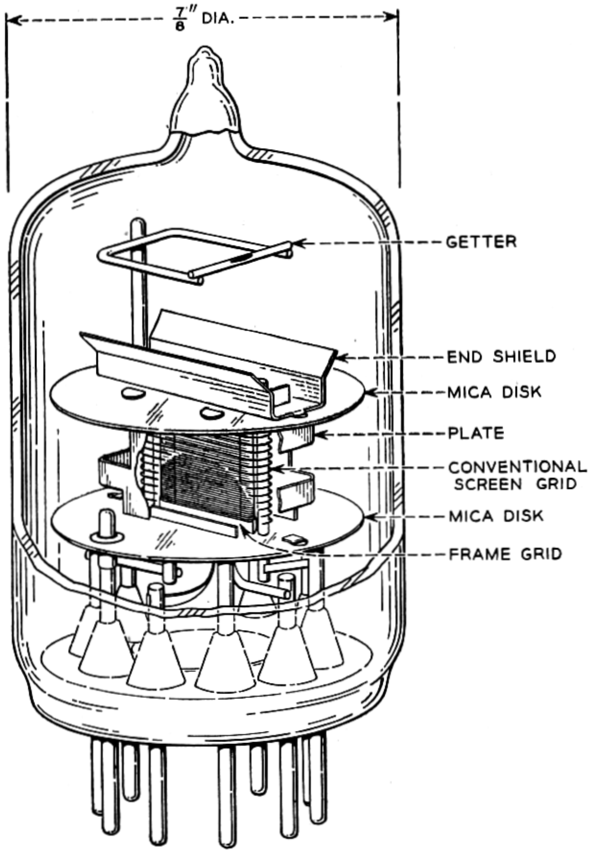

Fig. 9—Cutaway view of the 435A.

Figures 9, 10, and 11 are the cutaway views of the 435A, 436A, and 437A tubes. The overall dimensions of the L3 tubes are:

	435A	436A	437A
Max. seated height	$1\frac{1}{2}''$	$1\frac{5}{8}''$	$1\frac{5}{8}''$
Max. diameter	$\frac{7}{8}''$	$1\frac{3}{16}''$	$1\frac{3}{16}''$
Number of pins	9	9	9
Pin circle diameter	$\frac{15}{32}''$	$\frac{11}{16}''$	$\frac{11}{16}''$

Conventional construction for small repeater tubes may be thought of as two mica wafers between which are assembled the active elements of the tube. The mica wafers serve to support and space the tube elements. This mica and element assembly is then mounted upon a glass stem or platform which is next sealed into a glass bulb after which the exhaust and activation procedures complete the tube. These cutaway views show that these L3 system tubes are very similar to conventional tubes. The reason for wanting to continue with the conventional type structures is simply that of tube

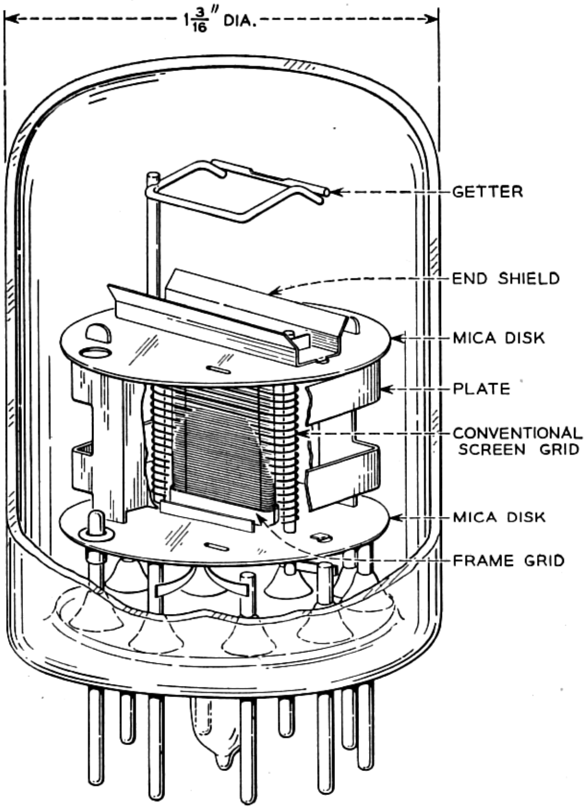

Fig. 10—Cutaway view of the 436A.

cost. A production line such as that for the W.E. 408A or 6AK5 tubes could very readily be changed over to any one of these tubes. The only change needed would be in the control grid supply and in the dimensional control procedures.

The principal distinctive design feature in these tubes, compared to earlier repeater tubes, is the "frame" type of control grid which was first introduced in a somewhat different form in the W.E. 404A[4] and W.E.

[4] "The 404A- A Broadband Amplifier Tube," G. T. Ford, *Bell Laboratories Record*, Vol. XXVII Feb. 1949.

418A tube. The L3 frame grids are illustrated in Fig. 12, together with a conventional control grid from the 6AK5 tube and the control grid from the 404A vacuum tube. The conventional grid consists of two large side rods, usually of nickel, around which is spirally wound the grid lateral wire. The lateral wire is joined to the side rod at each intersecting point by first knifing a groove into the side rod, laying the lateral wire into the groove,

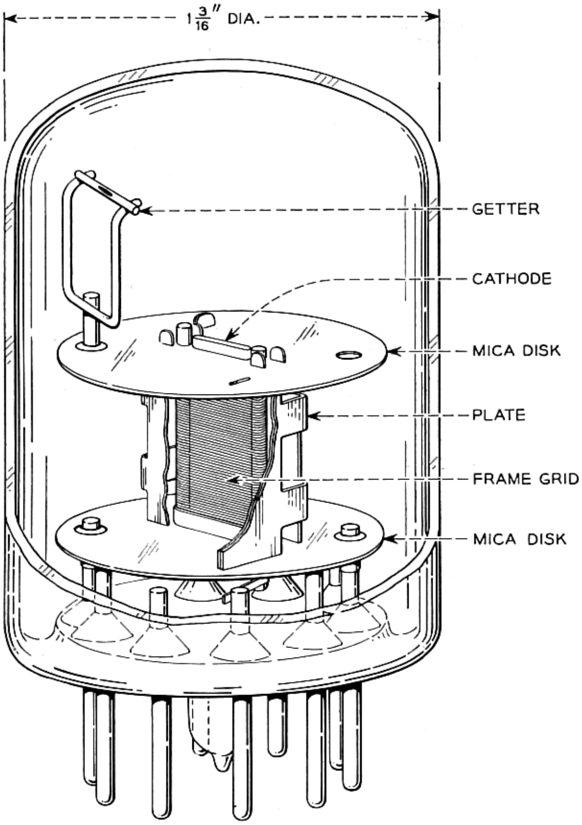

Fig. 11—Cutaway view of the 437A.

and then swaging the groove closed. Since, in these conventional grids, the lateral wire is usually larger than 0.0008″ diameter, the grid is self supporting and needs no strengthening members. For the high figure of merit tubes, control grid lateral wires of the order of 0.0003″ diameter are needed. Wire of this diameter is not self supporting in the necessary lengths and for that reason the two large side rods are first joined together by the cross straps which are located at the ends of the grid proper. These then form a rigid frame around which the very fine lateral wire can be spiraled without any danger of having laterals out of place. It can be seen that this technique produces the extremely flat grid plane which is necessary for the desired

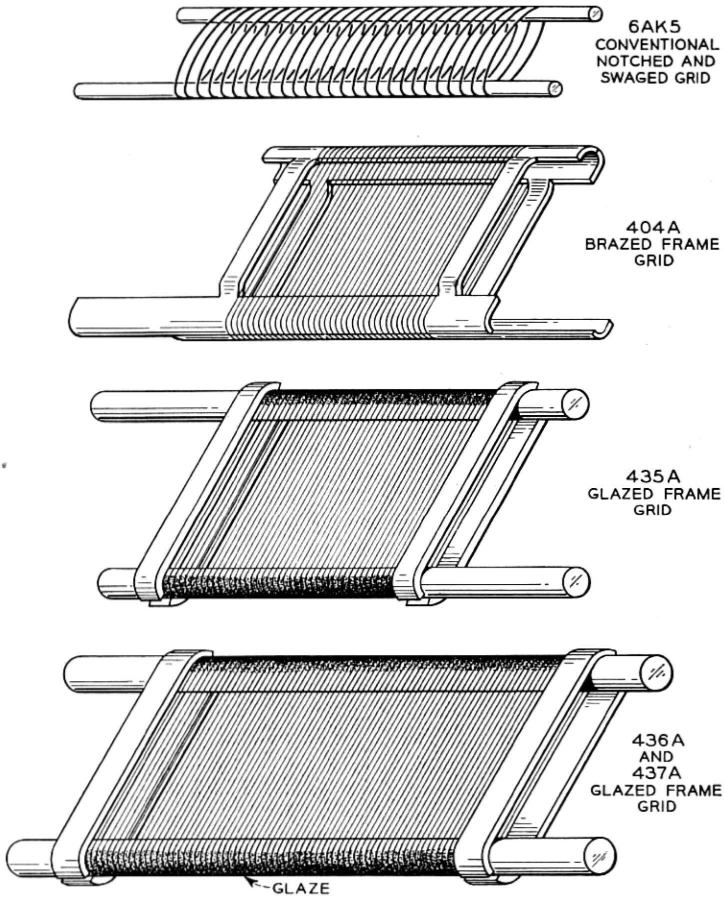

Fig. 12—Control grids for the 408A or 6AK5, the 404A and the L3 carrier tubes.

tube performance, and which is the real difference between these high figure of merit tubes and the more conventional tubes.

The fabrication of the 404A frame grid has been discussed in a previous article.[5] That article also mentioned the 418A grid which is a side rod type

[5] "Fine-Wire Type Vacuum Tube Grid," E. J. Walsh, *Bell Laboratories Record*, Vol. XXVIII April 1950.

frame grid. The L3 grids are a further development. The major difference between the earlier frame grids and these is in the method of bonding the 0.0003″ lateral wire to the side rods. In the earlier grids a gold braze was used to bond the laterals to the side rods. This necessitated heating the unit to approximately 1070°C to flow the gold. The newer grids have the lateral wires bonded by a glass glaze which allows the process to be carried out at approximately 700°C. There is a differential expansion between molybdenum and tungsten of about five to four. The net result of the reduction of temperature in this process is that the tungsten wires are stretched less at the lower temperature and thus when returned to room temperature have higher residual tensions. This is important because the higher the residual tension the higher the resonant frequency of the lateral wires. This in turn means that the noise level of the tube due to vibration or shock will be reduced since loose grid wires will give rise to microphonic noises. Tighter wires also decrease the possibility of grid to cathode shorts. Tests have shown that an increase of about 25% in the resonant frequencies of the lateral wires can be expected as a result of using the glass glazing technique as compared to the gold brazing technique.

It is interesting to note that the residual stress in the lateral wires of these grids is of the order of 200,000 pounds per square inch. This figure is roughly ten times as great as the allowable working stress for steel beams such as are used in the construction industry.

When the glazing technique is used, the grid is gold plated after the glazing operation has been completed. The gold is used to inhibit thermionic emission from the grid wires. This is a necessity for tubes of this type when used in the circuits for which they were designed. The need for the plating exists because of the proximity of the grid wires to the hot cathode and their unfortunately favorable position for receiving a deposition of active material from the cathode during its processing and operation. The desired amount of gold on the grid wires is that which will cause a diameter increase of about 0.00002″. This is an extremely difficult increase to measure because the measurement must be non-destructive, since it is made on the finished grid and is used as a production control. The method used to date has been an optical measurement at a magnification of about 500×.

A very high degree of precision, compared to that previously available, has been obtained for some of the parts whose dimensions are critical. The cathode sleeve is now obtainable with minor axis limits of ±0.0003″. The mica discs are now made with the critical holes to that same tolerance. The frame grid side rod is made to ±0.0001″. These are the basic elements of the tube and, after inspection has shown them to be acceptable, their assembly becomes close to that of a conventional tube. The inspection of these parts is difficult when production numbers are considered. The micas in particular presented a serious problem. Mica sheet is composed of a large number of laminations many of which are of the order of 0.0001″ in thickness. When the mica discs are punched out, these laminations leave, not smooth edge holes as do metal stampings, but rather a large number of minute jagged edges. The method used to check these was an optical one in which the mica was projected at about 40 times size onto a glass screen on which engraved lines acted as go-no-go gages. This reduced tool and human error considerably. The cooperation of several industrial concerns which supply some of the critical parts and the measuring instruments was very helpful in obtaining the desired tolerances.

It was evident from the start of the development of the L3 tubes that the performance requirements for high gain conventional structure tubes would be pushing to the limit the available process controls and measuring techniques. A statistical quality control program was put into effect on the tubes after the final laboratory design had been crystallized. The statistical study covered the tube dimensions and the data collected from those tubes after they had been processed. The net result of the study was to indicate that better measuring methods and process controls are needed.

With the amount of d-c. feedback employed in the working circuits, the space current does not vary too rapidly with tube geometry. In the case of the most critical spacing, that between the grid and the cathode, a 10% change in the spacing would be expected to cause only about 2.5% change in space current. However, the transconductance is more sensitive to the grid-cathode spacing, with a 14% change in transconductance to be expected for a 10% change in the spacing. This comes about because the transconductance is a function of the spacing, even at a fixed space current.

Since a 10% change in spacing is only 0.00025 inch, the importance of close tolerances on the parts dimensions controlling it is evident. The test specification limits on transconductance permit a variation of about ±25%, so that the 0.00025 inch change in spacing would use up over half of the allowed deviation. Preproduction runs at the Laboratories have shown that the tubes are practical and that their performance in the amplifier circuits has justified their design.

3.2 *Electrical Characteristics*

The nominal electrical characteristics are shown in Table II. The corresponding characteristics for the earlier types 386A, 6AK5 and 404A are also given for comparison. The last row in the table shows figure of merit values which are a measure of the circuit performance. The tabulated values for the figure of merit were calculated, taking into account the effect of space charge on the input capacitance, and include a total allowance of 3 mmf. for socket and wiring capacitance (input plus output). The L3 tubes are somewhat better than the 404A and substantially better than the 6AK5. The figures of merit tabulated will not check with the values shown in Figs. 2–4 since the curves were calculated for cold tube capacitances and zero socket and circuit capacitances.

Table II

Classification	386A Pentode	6AK5 Pentodes	408A	404A Pentode	435A Tetrode	436A Tetrode	437A Triode
Heater voltage	6.3	6.3	20.0	6.3	6.3	6.3	6.3 volts
Heater current	0.150	0.175	.05	0.30	0.30	0.45	0.45 amps
Plate current	7.5	7.5		13	13	25	40 ma
Screen current	2.5	2.5		4.5	3.5	8	— ma
Transconductance	4000	5000		12500	15000	28000	45000 μmhos
Input capacitance*	3.6	3.9		7.0	7.8	15.2	11.5 mmf
Output capacitance*	2.6	2.85		2.5	2.5	3.3	0.9 mmf
Plate-grid capacitance*	0.025	0.01		0.03	0.025	0.05	3.5 mmf
Figure of merit**	61	72		123	146	165	— mc

* Cold capacitances.

** This is the frequency at which unity voltage amplification would occur with a simple parallel tuned circuit interstage. Allowances have been made for stray capacitances and for the increase in input capacitance when a tube is energized. No figure is given for the 437A tube because the relations derived for the earlier stages in the amplifier do not apply to the output stage.

3.3 *Performance in Repeater*

The positions of the tubes in an auxiliary repeater are indicated in the diagram of Fig. 13. The overall insertion gain is a little over 30 db at 4 mc. While the noise contributions of the first 435A tube and the 436A tube are important, they have been reduced to 48 db below one volt and 62 db below one volt, respectively, for 1200 repeaters. The second 435A tube and the "lower" 437A tube appearing in Fig. 13 are the major contributors to the modulation. The expected modulation levels from these tubes are those associated with single tone ratios of about 34 db for the fundamental to second harmonic ratio and 70 db for the fundamental to third harmonic ratio, with a grid signal level of 0.1 volt r.m.s.

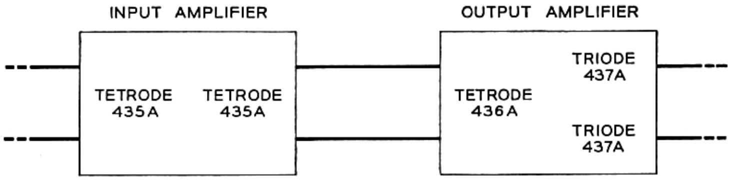

Fig. 13—Position of tubes in the input and output amplifiers for the L3 carrier system.

The gain-band performance in this repeater, or in any other circuit, will be less than that shown in the curves in Figs. 2–4 since the total shunt capacitances in a working circuit are always larger than the cold tube capacitances used in calculating the inherent figure of merit.

3.4 *Test Specifications*

The test specifications for the L3 tubes were written with the L3 system requirements as the prime consideration. In addition to the usual tests made on small tubes, a modulation test was included for the 435A and 437A tubes because of the importance of this characteristic in terms of system performance. In order to avoid penalties which can result from unwanted systematic deviations which pile up in a long system, requirements have been set up which will control the distribution of transconductance, modulation, and some of the most critical interelectrode capacitances. By the application of suitable quality control methods, it is expected that these requirements can be met economically and that such measures will prevent the manufacture of large numbers of tubes having average characteristics far off the design values. When simple go, no-go limits are used, it is not economical to set close enough limits to attain the desired control of the average characteristics.

4. Conclusions and Future Possibilities

The fundamental problem in the development of repeater tubes for broad band coaxial systems has been to devise means for utilizing closer and closer grid-cathode spacings without sacrificing life performance.

The closer spacings have been made possible by devising rigid control grid supporting structures which can be wound with very small diameter wire. The wire is held under tension by the supporting frame so that a flat winding is produced which can be spaced very close to a flat cathode.

The possibilities for the development of tubes which will provide still better broad band amplification depend to a great extent upon the kind of system design to be considered. If higher figure of merit, as defined in this article, can be utilized, considerable improvement can be realized with space charge controlled tubes such as the 435A, 436A and 437A by using mounting arrangements which provide more precise means of establishing and maintaining the critical dimensions.

Acknowledgements

Several members of the technical staff and their assistants have contributed materially in solving the numerous technical problems which arose during the development of these tubes. In addition, those who fabricated the grids and assembled the experimental tube models made important contributions in terms of skill and painstaking effort. It is not practical to name all of the persons involved.

The development of broad band tubes over the last fifteen years was under the direction of the late Dr. H. A. Pidgeon until 1943, and Mr. J. O. McNally from 1943 to date. The writers wish to acknowledge the importance of their helpful guidance and encouragement.

APPENDIX

Meanings of Symbols

F = Figure of merit
G = Voltage amplification
B = Bandwidth between 3 db points
K = Interstage circuit constant
G_m = Grid-plate transconductance
C_1 = Input capacitance
C_2 = Output capacitance
n = Turns per unit distance on grid
a = Grid-cathode spacing
b = Grid-screen spacing
c = Screen-plate spacing
A = Area of active structure
I_b = Plate current, d-c
M = Ratio of plate current to cathode current
E_{c1} = Grid-cathode voltage
E_{c2} = Screen-cathode voltage
μ = Grid-screen amplification factor
I_0 = Cathode current density, d-c
r = Grid wire radius
I_p = Amplitude of fundamental component of a-c plate current
I_{2p} = Amplitude of second harmonic component of a-c plate current
i_p = Fundamental a-c plate current component
i_{2p} = Second harmonic plate current component
G_0 = Perveance factor
E_g = Amplitude of grid signal voltage
p = Frequency $\times$ 2π
t = Time
i = a-c plate current

Units: length in cms; practical electrical units; time in seconds.

Assumptions

I

$$na = 1$$

The ratio of the pitch distance to the grid-cathode spacing is held constant. This is done so that the effect of the variation in field along the cathode surface resulting from the finite grid pitch distance will be small and the same throughout the discussion.

II

$$C_1 = 0.0885 \times 10^{-12} A \left(\frac{1}{a} + \frac{1}{b}\right)$$

$$C_2 = \frac{0.0885 \times 10^{-12} A}{c}$$

The input and output spaces are treated as if they can be represented by ideal condensers. This amounts to assuming that the grids are perfect planes and that there are no end effects. The effects of space charge on the capacitances are neglected, and the socket and wiring capacitances are also neglected. This means that the resulting calculated figure of merit represents the limiting value inherent in the tube structure.

III

$$I_B = \frac{2.33 \times 10^{-6} MA \left(\frac{E_{c2}}{\mu} + E_{c1}\right)^{3/2}}{a^2 \left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)^{3/2}}$$

The expression for plate current assumed is an idealized one, but holds fairly well for these tubes.

IV

$$\frac{d\mu}{dE_{c1}} = 0$$

It is assumed that the triode amplification factor is independent of the control-grid voltage. This holds fairly well under the conditions of assumption I.

V When the interstage consists of a single parallel tuned circuit, $K = 1$. This case is assumed.

Derivations

Beginning with the above assumptions, and substituting in equation (1), equations (2), (3) and (4) can be derived. The procedure will be outlined below:

$$F = \frac{KG_m}{2\pi(C_1 + C_2)} \tag{1}$$

$$F = \frac{4.74 \times 10^8 M I_0^{1/3}}{a^{4/3}\left(\frac{1}{a} + \frac{1}{b} + \frac{1}{c}\right)\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)} \tag{2}$$

$$E_{c2} = \mu\left[5.68 \times 10^3 a^{4/3} I_0^{2/3}\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right) - E_{c1}\right] \tag{3}$$

$$\mu = \frac{2.73\,\frac{b}{a} - \log_{10}\cosh\left(2\pi\,\frac{r}{a}\right)}{\log_{10}\coth\left(2\pi\,\frac{r}{a}\right)} \tag{4}$$

Substitutions for C_1, C_2, and K in (1) are made from assumptions II and V. G_m is found by differentiating the plate current expression (assumption III) with respect to E_{c1}, remembering that μ is independent of E_{c1} according to assumption IV.

$$G_m = \frac{3}{2}\,\frac{2.33 \times 10^{-6} MA\left(\frac{E_{c2}}{\mu} + E_{c1}\right)^{1/2}}{a^2\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)^{3/2}} \tag{5}$$

From assumption III we can write

$$\left(\frac{E_{c2}}{\mu} + E_{c1}\right)^{1/2} = \frac{I_B^{1/3} a^{2/3}\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)^{1/2}}{(2.33 \times 10^{-6})^{1/3} M^{1/3} A^{1/3}} \tag{6}$$

Substituting in (5)

$$G_m = \frac{3}{2}\,\frac{(2.33 \times 10^{-6}) MA I_B^{1/3} a^{2/3}\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)^{1/2}}{a^2\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)^{3/2}(2.33 \times 10^{-6})^{1/3} M^{1/3} A^{1/3}}$$

$$G_m = \frac{1.5(2.33 \times 10^{-6})^{2/3} M^{2/3} A^{2/3} I_B^{1/3}}{a^{4/3}\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)} \tag{7}$$

Since $I_B = MI_0A$ by definition,

$$G_m = \frac{2.64 \times 10^{-4} MA I_0^{1/3}}{a^{4/3}\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)} \tag{8}$$

Substituting in (1),

$$F = \frac{2.64 \times 10^{-4} MAI_0^{1/3}}{a^{4/3}\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right) 2\pi \left[.0885 \times 10^{-12} A \left(\frac{1}{a} + \frac{1}{b} + \frac{1}{c}\right)\right]} \tag{9}$$

Collecting the constants and cancelling the A's,

$$F = \frac{4.74 \times 10^{8} MI_0^{1/3}}{a^{4/3}\left(\frac{1}{a} + \frac{1}{b} + \frac{1}{c}\right)\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)} \tag{2}$$

The expression for E_{c2} can be found by substituting $I_B = MI_0A$ in assumption III and solving for E_{c2}.

$$MI_0A = \frac{2.33 \times 10^{-6} MA \left(\frac{E_{c2}}{\mu} + E_{c1}\right)^{3/2}}{a^2\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)^{3/2}}$$

$$\frac{E_{c2}}{\mu} + E_{c1} = \frac{a^{4/3} I_0^{2/3}\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right)}{1.76 \times 10^{-4}}$$

$$E_{c2} = \mu\left[5.68 \times 10^{3} a^{4/3} I_0^{2/3}\left(1 + \frac{1}{\mu}\frac{a+b}{a}\right) - E_{c1}\right] \tag{3}$$

The expression for μ can be found by applying assumption I and substituting $n = \frac{1}{a}$ in the Vogdes-Elder formula* for a plane structure.

$$\mu = \frac{2\pi nb}{2.303 \log_{10} \coth (2\pi nr)} - \frac{\log_{10} \cosh (2\pi nr)}{\log_{10} \coth (2\pi nr)} \tag{10}$$

Substituting $n = \frac{1}{a}$

$$\mu = \frac{2.73 \frac{b}{a}}{\log_{10} \coth \left(2\pi \frac{r}{a}\right)} - \frac{\log_{10} \cosh \left(2\pi \frac{r}{a}\right)}{\log_{10} \coth \left(2\pi \frac{r}{a}\right)} \tag{4}$$

Equation (11) can be derived by considering a particular structure and introducing a small sinusoidal signal $E_g \cos pt$ added to the d-c. voltage in the plate current expression, Assumption III. This can be written as

$$I_B + i = G_0\left(\frac{E_{c2}}{\mu} + E_{c1} + Eg \cos pt\right)^{3/2} \tag{12}$$

* F. B. Vogdes and Frank R. Elder, *Phys. Rev.*, 24, pp. 683–689, Dec., 1924.

For zero signal this becomes

$$I_B = G_0 \left(\frac{E_{c2}}{\mu} + E_{c1} \right)^{3/2} \tag{13}$$

For a pure resistance load which is small compared to the plate resistance, the fundamental component, neglecting contributions from third and higher order terms, is

$$i_p = G_m E_g \cos pt \tag{14}$$

Neglecting the contributions of fourth and higher order terms, the second harmonic component is

$$i_{2p} = I_B \frac{3}{16} \frac{E_g^2}{\left(\frac{E_{c2}}{\mu} + E_{c1} \right)^2} \cos 2pt \tag{15}$$

This is found by expanding (12) into the binomial series. From Assumption III and equation (5),

$$\left(\frac{E_{c2}}{\mu} + E_{c1} \right)^2 = \frac{9I_B^2}{4G_m^2} \tag{16}$$

The amplitude of the second harmonic component, from (15) is

$$I_{2p} = \frac{3}{16} \frac{I_B E_g^2}{\left(\frac{E_{c2}}{\mu} + E_{c1} \right)^2} \tag{17}$$

Substituting for $\left(\frac{E_{c2}}{\mu} + E_{c1} \right)^2$ from (16) in (17).

$$I_{2p} = \frac{G_m^2 E_g^2}{12 I_B} \tag{18}$$

From (14),

$$G_m^2 E_g^2 = I_p^2 \tag{19}$$

Substituting from (19) in (18),

$$I_{2p} = \frac{I_p^2}{12 I_B} \tag{20}$$

This can be written

$$\frac{I_p}{I_{2p}} = 12 \frac{I_B}{I_p} \tag{11}$$