KEVIN'S WEBSURFER HANDBOOK VII
FOR CRYSTAL RADIO

DEDICATED ENTIRELY to
VACUUM DIODES

Kevin Smith
2012

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KJ Smith

INTRODUCTION

The contents of this latest handbook, volume 7 already, is concerned exclusively with the subject of vacuum diodes. Crystal radio is already a hobby dominated by an interest in vintage and antiquated technology. Vacuum tubes are yet another aspect of vintage radio technology. Interestingly, the vacuum diode was invented and patented prior to the crystal detector, one year prior it is true, but the priority is there.

As a crystal radio hobbyist, my interest is in diodes and rectification, not amplification so no triode (or higher) type tubes are on the menu. My personal interest in tubes stems from a childhood of listening to classic tube radios. I had one on a small shelf next to my bed and would often lay awake in the dark listening to music (turned down low so my parents would not hear) and look at the red glow from the inside of the set. There was something reassuring about the glow, you knew the radio would work as long as the glow was there. Agreed, having to wait a minute or so while the radio "warmed up" before hearing anything could be at times frustrating. When your friends called and said to "quick, turn on the radio and listen to this...", well, it was probably already too late. I also recall the first transistor radio and how cool it was to have the sound come on instantly. Still, what goes around, comes around. I recently was showing my adult daughter a cool old tube radio I had purchased. I turned it on and, as usual nothing... We talked on a bit about the hobby and stuff when, as if by magic, the sound from the radio behind us came on. She, astonished, exclaimed that’s "So cool!". Novelty is always fun. I note that she didn't go out to buy herself a tube iphone.

As tubes pretty much went the way of the horse and buggy with the introduction of transistors, most, virtually all good technical information on vacuum tubes is vintage in nature. As such, I have conceived this handbook as a historical walk down memory lane as well as technical reference for those, like myself, who wish to add vacuum tubes to their crystal radio projects and need specific technical help. I open with the words of Fleming himself describing the valves' pedigree and his personal involvement as the inventor of the vacuum valve. From there I move quickly to useful references and analysis from the 1940's, the heyday of the vacuum era. For much this I am MOST indebted to Pete Millett's tubebooks.org for scanned reference works on tubes, (http://www.tubebooks.org/). I have only included those portions of documents directly concerned with diode theory and operation. For your interest in triodes and amplification, I encourage you to visit Pete yourself.

I also include a good recent treatise on vacuum tubes by Calvert in 2003, (also included in my Handbook III on Diodes). And finally some of my own measurements, graphs, and notes on a selection of vacuum tubes I have acquired and played with.

While much of the material in this handbook is way out of copyright, some is and I have not sought permission. Therefore this is not presented for publication or copy, and certainly not for profit. It is only my personal resource. I encourage anyone finding this copy to pursue ON THE WEB the web pages identified, especially tubebooks.org. I wish to sincerely thank every author presented for their excellent pages and ask forgiveness for my editing into this handbook.

Kevin Smith
2012

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expressed its real potential. The evidence is given by modern formulation designs wich, often join even in concepts going back to the dawning of electronics (as well as harmonic cancellation, feed-forward, tansformer coupling, choke input filter etc.), can produce sonic results higher than the crowd of Williamson-like amplifiers.

References:

[1] Charles Rydel SIMULATION OF ELECTRON TUBES WITH SPICE", AES preprint 3887 (G-2), 98th AES Convention, Paris 1995;

[2] Scott Reynolds VACUUM TUBE MODELS FOR PSPICE SIMULATIONS, GLASS AUDIO n. 4, 1993

[3] W. Marshall Leach, Jr SPICE MODELS FOR VACUUM TUBE AMPLIFIERS, JAES March 1995

[4] Norman Koren IMPROVED VT MODELS FOR SPICE SIMULATION, GLASS AUDIO, N. 5 1996

[5] F. Langford-Smith Radiotron Designer's Handbook, 4th Ed. 1953

[6] Piotr Mikolajczyk Bohdan Paszkowski Universal Electronic VadeMecum

Condenser input filter		
	MEASUREMENT RESULTS	SIMULATION RESULTS
Vout	146.62Vcc	144.74Vcc
Repetitive peak current	70.59mA	68.21mA
Ripple Percentage	4.09%	4.14%
Choke input filter		
	MEASUREMENT RESULTS	SIMULATIONS RESULTS
Vout	101.320Vcc	101.116Vcc
Repetitive peak current	14.02mA	13.66ma
Ripple Percentage	0.52%	0.75%

Tab. 6;

Vin1, Vin2@120Vrms;
R1= R2= 6.8 ohm;
L1= 30H in choke input filter power supply;
C1= 8.10 mcrF;
Rl= 10.16K;
12X4 vacuum-diode.

The 12X4 SPICE model whose parameter have brought in line 1 of Table 3 have been drawn just from the real diode used for the construction of two power supplies (here explained the reason for the apparent redundance in Tabb. 1, 2, 3). So here I won't make a comparison on the grounds of a model drawn from the average characteristics, but with reference to a Sylvania's 12X4 sample. The utmost closeness of the numerical results in Table 6, makes me rather optimist about the validity of the implemented model; to the small differences that you can recognize, partly contribute also the errors of the measurement process in real world.

Conclusion

I hope this article can add a small wedge to the big mosaic of the circuit simulation applied to vacuum tube amplifiers. I believe the thermionic technology applied to the audio has not yet totally

THE THERMIONIC VALVE

AND ITS DEVELOPMENTS IN RADIOTELEGRAPHY AND TELEPHONY

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THE THERMIONIC VALVE AND ITS DEVELOPMENTS IN RADIOTELEGRAPHY AND TELEPHONY

CHAPTER I.

Historical Introduction.

1. The thermionic valve and its various derivatives, such as the three-electrode amplifier and also the thermionic oscillation generator, have become such valuable appliances in wireless telegraphy that it would seem to be an advantage to collect into a single volume a brief summary of knowledge and practice connected with them for the assistance of practical radiotelegraphists. An additional reason for endeavouring to present an unsophisticated description of the nature and mode of operation of these radiotelegraphic instruments is that much which has been written on the subject, especially in patent specifications, has had the effect of obscuring rather than elucidating the true scientific facts connected with the operation of this type of detector or generator.

Small modifications of the original instruments have been christened, especially in the United States, by many strange and fanciful names, and a vocabulary has been developed which makes it difficult for the uninitiated to discern the physical principles involved, although it may have some advantages in inducing Patent Office Examiners to accept as fresh contributions to invention implements or arrangements destitute of real novelty.

The statement of the various stages by which inventors have produced appliances of great sensitivity for the detection of electromagnetic waves forms a fascinating chapter in the history of electrotechnics. Although Maxwell

1 B

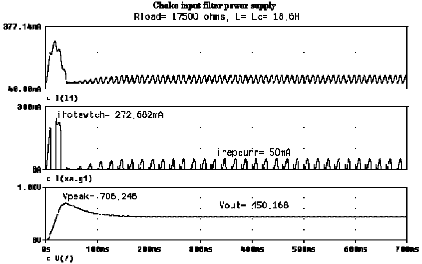


Fig. 11;

As you can observe in Fig. 9 it is rather easy to overcome the limits related to the impulsive currents also with small input condensers therefore their capacitive value has to be valued very attentively. Besides Fig. 11 reveals that the swinging choke calculus is not very accurate.

An actual comparison

In Table 6 I present the results of two simple power supplies with condenser and choke input filter respectively. Schematics are the same of Figs. 9 and 10 but with the following differences:

Condenser input filter power supply

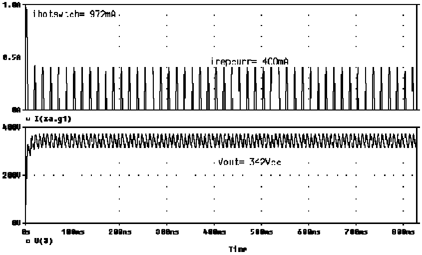


Fig. 9;

Choke input filter power supply

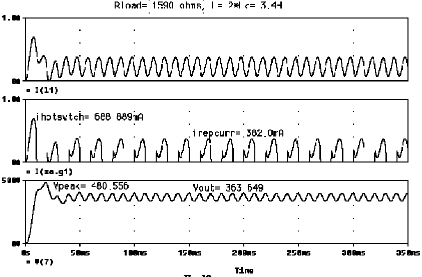


Fig. 10;

enunciated in 1865 his great epoch-making theory that electromagnetic effects must be propagated through dielectrics as a wave motion, and surmised that such electromagnetic radiation was identical in nature with light, the acceptance of his views was retarded by the want of experimental proof that such waves could be created and detected by purely electromagnetic methods. Hertz's invention of the ring resonator with micro-spark gap supplied the first means of detecting these space waves, which G. F. Fitzgerald had previously suggested might be created by the oscillatory discharge of a Leyden jar. The employment of Maxwell's electromagnetic waves to effect radiotelegraphy, involving the propagation of such waves over distances reckoned in miles, was fundamentally dependent on Marconi's key invention of the aerial wire or antenna, but it necessitated as well the possession of far more sensitive and certain means of detecting these waves than the ring resonator of Hertz.

In radiotelegraphy we make use of electromagnetic waves propagated over the earth's surface to set up in a receiving aerial wire feeble electric oscillations which are a copy on a very reduced scale of the strong oscillations created in the sending aerial wire. In modern radiotelegraphy the oscillations are generated in the aerials either continuously or else in uniformly time-spaced trains, the train or group frequency agreeing with that frequency for which the Bell telephone receiver, acting on the human ear, is most sensitive —viz., about 300-500 per second. These oscillations are then cut up into short and long periods or groups of trains to create the Morse-code signals.

In the ordinary language of wireless telegraphy we call any instrument a *detector* which is employed to detect or make evident by audible or visible means these groups or intermittencies of very feeble electric oscillations in the receiving aerial wire and associated circuits which convey the intelligible signals.

The signal-making instrument may be some form of telegraphic printer, such as the Kelvin syphon recorder or the Morse inker, or the more sensitive Einthoven galvanometer with photographic tape record. On the other hand it may be a Bell telephone receiver, making an audible sound and appealing therefore directly to the ear. In any case the detector plays an intermediary part. It is operated upon by the feeble oscillations in the receiving aerial, and in turn it acts upon and operates the signal-making instrument.

2. If we leave out of account certain not very sensitive types of detector, such as the thermo-electric, the electro-dynamic or the vacuum tube, which have important uses in the laboratory, but are not sufficiently sensitive for radiotelegraphic work, we may say that five great types of detectors have so far been employed in radiotelegraphy.

These are, *first*, the imperfect contact or coherer type. Starting with the early forms invented by Branly and Lodge, and others, we have as the best representative of this class the nickel-silver filings coherer of Marconi.

The imperfect contact detectors are divisible into two sub-classes—viz., those which require tapping or moving to continually restore them to the sensitive condition, and those that are self-readjusting. The Marconi coherer is one of the first kind, and the Italian Navy carbon-mercury or Castelli coherer, and also the Walter tantalum-mercury coherer, represent the second or automatic sub-class.

In spite of the fact that the Marconi coherer did splendid service for at least five years in establishing radiotelegraphy on a practical basis, these contact detectors have all gone out of use at present. The numerous and delicate adjustments required in the tapper, relay, and Morse inker to obtain the best results, and the too ready response of the detector to atmospheric discharges, or to disturbances from the neighbouring transmitter and consequent variable sensitiveness, combined to bring about its antiquation and retirement from active service.

The *second* type of detectors comprises the magnetic detectors. Developed originally by Rutherford, E. Wilson and Marconi, we find again that the best practical representative of this type is the rotating iron band magnetic detector of Marconi.

This last detector employs a telephone receiver as the signal-making instrument. It has many virtues. It is robust, self-contained, and contains no supplementary or local battery. It is not put out of adjustment by atmospheric discharges or oscillations set up by the near-by transmitter. It is more constant in operation than the

Rs= total effective plate supply impedance per plate.

Condenser input filter		
	RADIOTRON'S RESULTS	SIMULATION RESULTS
Vout	350Vcc	342Vcc
Repetitive peak current	375mA	400mA
Ripple Percentage	5.5%	7.79%
Choke input filter		
	RADIOTRON'S RESULTS	SIMULATION RESULTS
20mA Load L=18.6H		
Vout	449Vcc	450.160Vcc
Repetitive peak current	40mA	50ma
220mA Load L=3.4H		
Vout	350Vcc	363.649Vcc
Repetitive peak current	330mA	302mA

Tab. 5;

In Table 5 I show a comparison between manual calculations (as brought in the Radiotron's) and simulations. The more meaningful graphic representations of such simulations are brought in Figg 9, 10, 11.

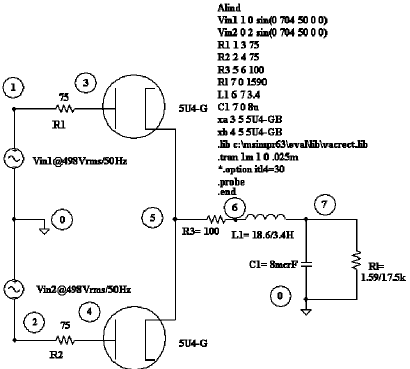


Fig. 8;

In Figg. 7 and 8 I have brought two hypotheses of power supply with condenser and choke input filter respectively together with their SPICE codes related to present examples beginning from the pages 1174 and 1183 of the Radiotron Designer's Handbook. The resistances R1 and R2 are the total effective plate supply impedance per plate and they represent the impedances brought to every secondary winding according to the formula:

Rs= Rsec + N2 * Rpri;

where:

N= Voltage ratio of transformer at no load (primary to half secondary in case of full-wave rectification);
Rpri= Resistance of primary winding in ohms;
Rsec= Resistance of secondary windind in ohms (or half secondary in case of full-wave rectification;

capricious coherer, but it is not one of the most sensitive detectors. Nevertheless, for military or ship work it is still much valued, although not very light in weight.

The *third* class of detector comprises the electrolytic detectors in which the electrical oscillations to be detected are caused to alter the conductivity of an electrolytic cell by varying the ionic films on the electrodes. These detectors have never come into very extensive use in Great Britain.

The *fourth* type of detector, and until lately probably the most extensively used, are the rectifying contact or crystal detectors. Starting with Dunwoody's discovery of the rectifying property of certain crystals of carborundum and with the discoveries of Pickard and G. W. Pierce on the rectifying power of contacts between crystals of zincite and chalcopyrite and molybdenite and copper, there has been an immense amount of research on this type of detector, which depends either upon a true unilateral conductivity in the mass or at the contact or else upon sudden changes in curvature in the volt-ampere or characteristic curve.

The simplest mode of use of such crystal detectors is as rectifiers of the oscillation trains into gushes of electricity in the same direction, thus enabling trains of electrical oscillations to affect a telephone receiver. These detectors are rather easily put out of adjustment by strong atmospheric discharges, or by strong oscillations set up by the proximity of the transmitter. They therefore require somewhat frequent readjustment of contact to obtain the best results. Nevertheless, their sensitiveness, simplicity and cheapness made them very quickly a favourite detector. Their introduction was followed at once by an outburst of irresponsible radiotelegraphy at the hands of innumerable electrical amateurs and students which required the firm intervention of National and International legislation to keep it within bounds of reason and safety.

The *fifth* class of detector comprises those to the consideration of which this book is limited—viz., the thermionic detectors. These depend ultimately upon the emission from incandescent bodies of ions or electrons. They are or can be made highly sensitive and yet are not affected injuriously by atmospherics or by neighbouring electric sparks. They are easy of adjustment and always ready for use. The original of all these detectors is the now well-known Fleming

Valve. They have the remarkable property that they can be employed as generators of oscillations as well as detectors and have important uses as telephone repeaters and ordinary telegraph relays, in addition to services in wireless telegraphy. Hence their properties, construction and use have been widely studied, and we may without risk of contradiction call them the master weapon of the radiotelegraphist.

3. It will be advisable to begin the study of these thermionic detectors by a short historical sketch of certain investigations and their results. About 1880 Mr. Edison completed his solution of the problem of domestic electric lighting by giving to the world the carbonised bamboo filament incandescent electric glow lamp, and Sir Joseph Swan, aided by Mr. C. H. Stearn, had evolved the parchmentised cotton thread lamp on similar lines. This simple appliance, consisting of an hermetically closed and highly exhausted glass bulb, having in it a carbon filament welded to terminal platinum wires sealed through the glass, solved the problem of "dividing the electric light" which had engaged the attention of numerous inventors for a quarter of a century. In the early part of 1882 the public had the opportunity of seeing at the first Crystal Palace Electrical Exhibition incandescent lighting on a large scale. The author of this book was at the beginning of that year appointed scientific adviser to the Edison Electric Light Company of London, formed to operate Edison's inventions in Great Britain, and came therefore into a position to investigate carefully some of the problems connected with the physics of the incandescent lamp.

It was soon found that, apart from accidents, such lamps had a certain "life." The slightest inequality in resistance of parts of the filament caused unequal production of heat, and any minute crack or flaw in the filament caused local superheating at that point and hence an excessive rise of temperature.

Even if the filament was extremely uniform there appeared to be a slow volatilisation of the carbon, which in time blackened the inside of the bulb and reduced the candle power of the lamp.

Before long the author's attention was drawn to the fact that when a defect appeared at some point in the carbon filament on one "leg" of the horseshoe carbon, which caused

calculations and formulae just finalized to the solution of actual situation. Other texts I know lack suitable depth or face the subject in a too academic way not enough finalized to the solution of real problems. On the contrary in the Radiotron's by fast procedures it is possible plan power supplies with both condenser input filter and choke input one. Unfortunately the accuracy, especially in the evaluation of the impulsive currents, is not high but this is due to the use of purposely approximate formulae to have agile calculation that at the time were made by the hand. Besides the book introduces two levels of approximation if you have complete data or not.

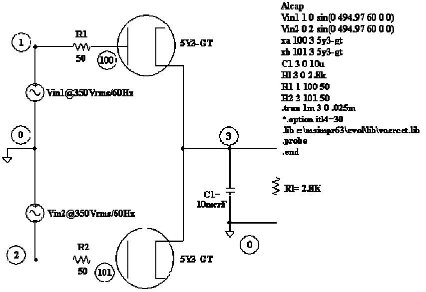


Fig. 7;

Now you can use the data in Table 3 to build the SPICE model of the diode. After the excellent articles by Raynolds [2], Marshall [3] and Koren [4], I don't think you will find any difficulty to understand the code in Table 4. The only required operation is to use the information in Table 3 and complete the code in Table 4 on the grounds of the selected diode.

```
.SUBCKT tubename P K
+ PARAMS Ka=       Kb=
+ A=       Eps=
E1              1  0   VALUE = {Ka + Kb * V(P,K)}
RE1   1  0    1G
E2              2   0   VALUE = {V(P,K) + EPS}
RE2   2   0    1G
G1              P     K       VALUE = {V(1)/2 * (PWR(V(2), A) +
PWRS(V(2), A))}
RPK      P   K    1MEG
* CPK   P   K     .5n
.ENDS
```

(*) CPK can replace RPK in case of serious convergence problems.
Tab. 4

How use this models

The first reason that can push you to look for an accurate model of vacuum diode is that, you can determine, when the device is used as a rectifier, a series of parameters whose exact evaluation can be either difficult or inaccurate as for istance the repetitive peak current, the hot-switching current, the output impedance etc. Besides the SPICE model you need further informations to place the device in safety areas. These informations are graphically available in Data-Sheets Rating Charts. In my opinion the Radiotron Designer's Handbook magistrally deals with the subject as it faces the whole problem list merely in engineering terms and therefore with

a great rise of temperature at that point, the blackening of the interior of the bulb was less or absent along a certain line in such fashion as to show that the scattered carbon molecules had been shot off in straight lines from the point of excessive heating. Thus was formed what the author termed *a molecular shadow* on the bulb (see Fig. 1). If, for instance, a scent-sprayer is filled with ink and the spray blown on to a sheet of paper the latter will be darkened uniformly by minute drops of ink spray. If, however, a wire or rod is held in the path of the spray the paper will be protected from blackening along a region which corresponds to the shadow of the rod (see Fig. 2). Hence when we find in old carbon filament incandescent lamps a horseshoe filament broken at one spot and the bulb darkened all over the inside with the exception of a white or undarkened line on the bulb corresponding to the shadow of the unbroken part of the filament relatively to the point of rupture or overheating we can conclude that the chief part of the scattering of the carbon particles has taken place in straight lines proceeding from the point in the filament at which it has ultimately burnt through. This phenomenon of "molecular shadows" in incandescent lamps was described by the author in two papers read to the Physical Society of London in 1883 and 1885.[1]

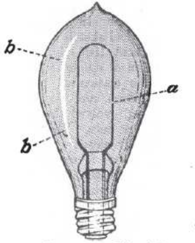


Fig. 1.—Incandescent Electric Lamp, showing the glass bulb blackened by the deposit of carbon or metal due to molecular scattering from point *a* on the filament, a shadow line of no deposit being formed at *b*, due to shielding effect of one leg of the horseshoe filament.

This effect clearly showed that from the incandescent

[1] See *Proc. Phys. Soc. Lond.*, vol. v., p. 283, 1883, "On a Phenomenon of Molecular Radiation in Incandescent Lamps," by J. A. Fleming; also *Proc. Phys. Soc. Lond.*, vol. vii., p. 178, 1885, "On Molecular Shadows in Incandescent Lamps," by J. A. Fleming.

filament there was a projection of matter in straight lines which was deposited on the interior of the bulb, except in those parts shielded by the "shadow" of the rest of the filament, thus leaving a white or unblackened line. This effect is obviously due to the fact that the residual air in the bulb is at such a rarefied condition that the mean free path of a molecule is comparable in length with the diameter of the bulb.

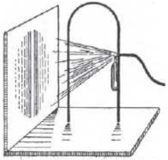


FIG. 2.—A "spray shadow" of a rod thrown on a cardboard screen by ink spray to illustrate the mode of formation of a molecular shadow in a glow lamp.

In air at ordinary temperature and pressure the mean free path of an oxygen or nitrogen molecule is about four one-millionths of an inch, but when the pressure is reduced in a bulb to one-millionth of an atmosphere it becomes increased to about four inches. This means that a molecule of carbon projected in any way from the filament might travel on an average four inches before colliding with other residual air molecules and being deflected from its path.

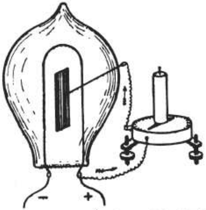


FIG. 3.—Incandescent Lamp with a Metal Plate sealed into the bulb and a galvanometer connected between the terminal of the plate and positive terminal of the filament to show the "Edison effect."

The next important observation on this subject was made by Mr. Edison in 1883.[1] He was apparently examining the phenomena involved when carbon filament lamps are running at a high efficiency, and for that purpose he sealed into the bulb of a glow lamp a metal plate placed between the legs of the horseshoe-shaped carbon filament, the

[1] See *Engineering*, December 12th, 1884, p. 553.

TUBE	Ka	Kb	A	S	R	EPS
12X4	0.0012211740	0.0004520104	0.550030857	0.00045660	0.99974709	0.1
5R4-GY	0.0031955387	0.0003869090	0.524866090	0.00207772	0.99995736	0.1
5U4-GB	0.0022026705	0.0005317449	0.572700700	0.00268508	0.99997075	0.1
5Y3-GT	0.0017537623	0.0001123292	0.662912440	0.00192639	0.99982758	0.1
6X5	0.0010419270	0.0001093351	0.910304640	0.00106960	0.99900026	0.1
EZ80	0.0013191127	7.3101291E-5	1.036858200	0.00065824	0.99997379	0.1
EZ81	0.0041960367	0.0002029324	0.914040040	0.00299013	0.99972150	0.1
EZ90	0.0012868566	0.0003271238	0.687482610	0.00184414	0.99980700	0.1
GZ30	0.0036003300	0.0016926165	0.447792260	0.00150959	0.99990710	0.1
GZ33	0.0064960776	0.0025909024	0.547065350	0.00145744	0.99986647	0.1
GZ34	0.0065731030	0.0003454340	1.004752200	0.00200713	0.99995540	0.1
GZ37	0.0000000000	0.0013172000	0.366156050	0.00306190	0.99981341	0.2
GZ40	0.0002655524	0.0004453651	0.535777180	0.00057510	0.99994085	0.1
GZ41	0.0015812518	6.3603057E-5	1.031013400	0.00046817	0.99992563	0.1

Tab. 3; Results for $I_p = (Ka + Kb \cdot V_p) \cdot (V_p + EPS)^A$ model

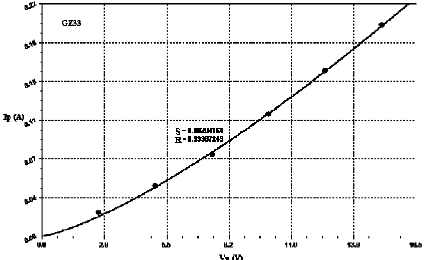


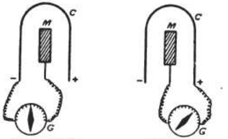
Fig. 6;

Finally you can get an even better fitting if you use the following equation:

$$Ip = (Ka + Kb*Vp)*(Vp + EPS)A \quad (3).$$

The equation (3) differs from (2) because a linear variation to the perveance has been attributed with respect to Vp. The application of LSM with linear regression leads to the data in Table 3. You can get further short improvement margins using more sophisticated mathematical models although this injuries simplicity and brings larger problems of convergence in simulations.

plate being carried on an insulated wire sealed through the bulb (see Fig. 3). He found that, when the filament was rendered incandescent by a direct current of electricity, a galvanometer connected between the middle plate and the positive terminal of the filament indicated a current of a few milliamperes, but little or no current when connected between the negative terminal and the middle plate (see Fig. 4). He did not furnish any explanation of this effect at that time, but it became known then and after as the "Edison effect" in glow lamps.



(No current) (A current)

FIG. 4.—Mode of connection of the galvanometer, *G*, to metal plate, *M*, and to the terminals of the carbon filament of the lamp (+and−) in the experiment of the "Edison effect."

Mr. Edison gave to Sir William Preece in October, 1884, certain incandescent lamps made with metal plates sealed into their bulbs or into tubular extensions of them, and in the following year, in March, 1885, Preece described to the Royal Society of London experiments which he had made with these lamps.[1] Preece made quantitative measurements of the current flowing through the galvanometer when connected in between the positive terminal of the carbon filament and the middle plate at various voltages applied to the filament. He found that this current was independent of the nature of the metal of which the middle plate was made, but that it increased very rapidly with increase in the potential difference of the filament terminals. He found that for a given lamp voltage the Edison effect varied with the position of the plate in the bulb, but that it was still sensible when this plate was placed at the closed end of a tube opening out of the bulb, provided this tube was straight, but the current was found to vanish if that side tube was bent up at right angles (see Figs. 5 and 6).

[1] See *Proc. Roy. Soc. Lond.*, vol. xxxviii., p. 219, 1885, "On a Peculiar Behaviour of Glow Lamps when Raised to High Incandescence," by W. H. Preece.

RADIOTELEGRAPHY AND TELEPHONY

Preece considered that this Edison effect was connected with the discharge or projection of carbon molecules or particles from the filament in straight lines, but he gave

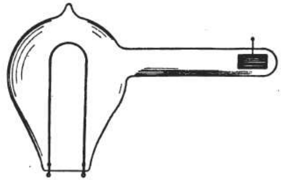


FIG. 5.—Collecting Plate placed at the end of a side tube opening out of the bulb of an incandescent lamp.

no full theory of the phenomenon, nor did he make any application of the facts. A year or two later the author of this book took up the investigation, being convinced that much yet remained to be discovered about it which had not been unravelled by Edison or Preece.

A number of special carbon filament glow lamps with middle plates were made for the author at the Lamp Factory of the Edison and Swan United Electric Light Company and researches were begun with them, and the results communicated to the Royal Society of London in 1889.[1] and in a Friday evening

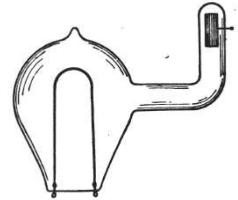


FIG. 6.—Collecting Plate placed at the end of an elbow tube opening out of the bulb of an incandescent lamp.

[1] See *Proc. Roy. Soc. Lond.*, vol. xlvii., p. 118, 1890, "On Electric Discharge between Electrodes at Different Temperatures in Air and in High Vacua," by J. A. Fleming.

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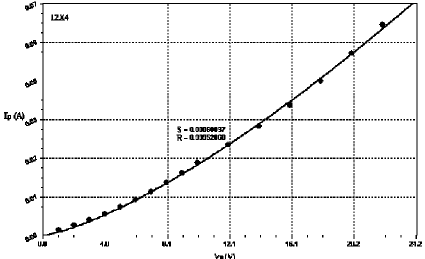


Fig. 4;

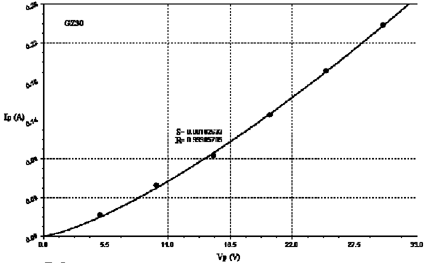


Fig. 5;

TUBE	K	A	S	R	EPS
12X4	0.008775603	1.3693599	0.00060837	0.99952060	0.1
5R4-GY	0.000673836	1.4214962	0.00324640	0.99988644	0.2
5U4-GB	0.007051655	1.5203189	0.00358406	0.99995741	0.2
5Y3-GT	0.000326542	1.4606772	0.00273940	0.99960771	0.2
6X5	0.000649553	1.5190353	0.00183847	0.99962271	0.2
EZ80	0.000549020	1.5792666	0.00144462	0.99974752	0.2
EZ81	0.001864868	1.4770666	0.00540127	0.99883198	0.008
EZ90	0.000575947	1.5583772	0.00177745	0.99976094	0.1
GZ30	0.002570010	1.3436975	0.00102633	0.99985705	0.1
GZ33	0.005317957	1.3349462	0.00204164	0.99967243	0.1
GZ34	0.002943400	1.5969530	0.00668603	0.99970154	0.1
GZ37	0.001325449	1.3640025	0.00304527	0.99981502	0.01
GZ40	0.000485414	1.5155771	0.00055090	0.99993797	0.1
GZ41	0.000915285	1.4108217	0.00074455	0.99976487	0.1

Tab. 2; Results for the $I_p = K*(V_p+EPS)^A$

to apply LSM to the set of experimental data. The results of this procedure have quoted in Table 2. EPS represents a parameter that can be manually fixed (typical values are 0.1, 0.2) used to guarantee a better convergence of the algorithm. If you compare the Correlation Coefficient of the Table 1 and 2, you can note a real amelioration, underlined subsequently by the new graphic representations of the tubes 12X4, GZ30, GZ33 related in Figg. 4, 5, 6. Futhermore the examination of Table 2 reveals that the real diode is subjugated by the 3/2 power law only in few cases.

discourse on February 14th, 1890, to the Royal Institution.[1]

One of the first new facts the author discovered was that the "Edison effect" was greatly diminished or entirely annulled by surrounding the negative leg of the carbon filament by a glass or metal tube, or by interposing a mica shield between the negative leg of the horseshoe-shaped carbon filament and that side of the middle or insulated plate facing the negative leg (see Figs. 7, 8 and 9). By negative leg is meant that side of the carbon horseshoe loop in connection with the negative pole of the battery which heats the filament. It was not annulled or much diminished when the tube surrounded the positive leg.

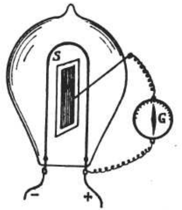


FIG. 7.—Incandescent Lamp having a mica shield placed between the metal plate, *M*, and the negative leg of carbon loop filament, thereby diminishing the "Edison effect."

The author confirmed Preece's observation that the effect

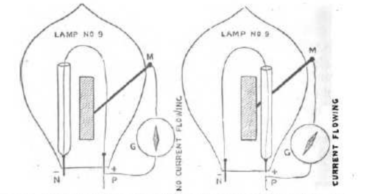


FIG. 8.—Glass or Metal Tube surrounding one leg of horseshoe carbon filament in a glow lamp to show the annulment of the "Edison effect" when it surrounds the negative leg.

[1] "Problems in the Physics of an Electric Lamp." *Proceedings of the Royal Institution*, February 14th, 1890.

was still visible when the collecting plate was placed at the end of a long straight tube opening into the bulb, but disappeared when the plate was placed at the end of a tube bent at right angles (see Figs. 10 and 11). The next fact discovered by the author was that a charged electric conductor or electric condenser if charged with positive electricity is instantly discharged when connected to the middle plate when the lamp filament is incandescent. If, however, the conductor or condenser is charged with negative electricity, then it is not in the least discharged by so connecting. On the contrary, it will be charged negatively by the incandescent filament.

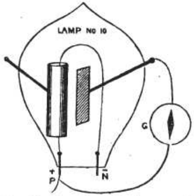


FIG. 9.—Incandescent Lamp with horseshoe carbon filament and metal cylinder surrounding one leg of filament to show the "Edison effect."

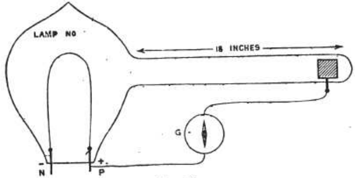


FIG. 10.

This fact may be most clearly proved by the following experiment. Connect a gold-leaf electroscope to the middle plate of the lamp, the filament being cold. Then charge the electroscope with positive electricity by means of a rubbed glass rod. Next, switch on the lamp and incandesce

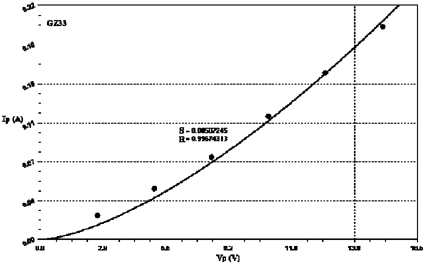


Fig. 3;

Improvement

You can already get a large improvement by varying the exponent of the equation (1). This leads to the following expression:

Ip= K*VpA.

Now use this equation, but modified in the following way:

Ip= K*(Vp+EPS)A (2)

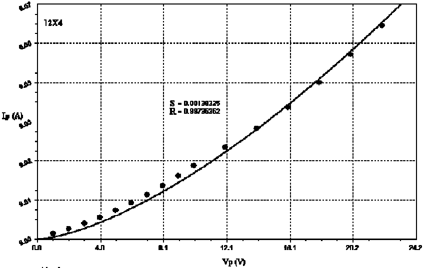


Fig. 1;

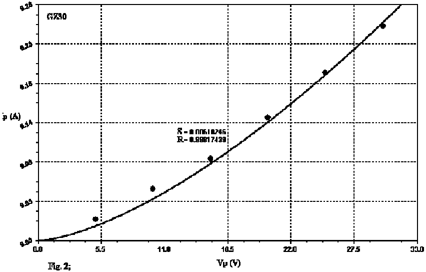


Fig. 2;

the filament. The electroscope instantly loses its positive charge. Then repeat the experiment, charging the gold leaves negatively by means of a rod of sealing wax, and it will be found that switching on the lamp does not discharge the electroscope. These experiments show that the incandescent filament is giving off negative electricity in some manner.

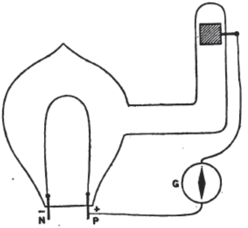


FIG. 11.

The next experiment was arranged to prove that the space between the incandescent filament and the middle plate was conductive for negative

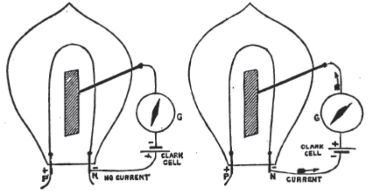


FIG. 12.—Incandescent Lamp with metal plate in the bulb and galvanometer, G, connecting plate and negative terminal. Clark cell inserted in plate circuit to show the escape of negative electricity from the incandescent filament.

electricity from the filament to the plate, but not in the opposite direction. For this purpose a single cell of a battery was joined in series with a galvanometer and one terminal attached to the middle plate and the other (the negative) terminal of the battery to the filament (see Fig. 12). A current then flowed through the vacuous space between the filament and the plate under this feeble E.M.F. of about 1·5 volts. If, however, the battery was reversed no current flowed.

A variation of this experiment was then arranged as follows :

A lamp was constructed, having four horseshoe carbon filaments in it, two at each end (see Fig. 13). These pairs

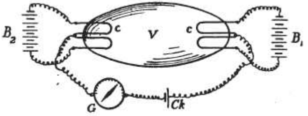


FIG. 13.—Exhausted Glass Bulb having terminal electrodes formed of carbon filaments kept incandescent by separate batteries to show the conductivity of a highly rarefied gas for currents of electricity under low electromotive force with an incandescent cathode.

could be joined in series outside the bulb, and each pair incandesced by its own insulated battery. When both sets of filaments were cold a small E.M.F., such as 8 or 10 volts or so, or even 100, would not send any measurable current across the vacuous space. If, however, the filaments at one end were made incandescent, then even a single cell can send a current of a milliampere or so through the vacuous space provided that this cell has its negative terminal in connection with that carbon filament which is incandescent. This fact had previously been discovered in another way by W. Hittorf[1]—viz., that through a vacuum tube a very small E.M.F. will send a measurable current, provided the cathode terminal of the vacuum tube is incandescent or at a high temperature.

The author then discovered that the same effects exist in the case of the electric arc.

[1] See *Annalen der Physik*, vo. xxi., p. 90, 1884 ; see also *Physical Memoirs*, vol. i., p. 180, issued by the Physical Society of London, W. Hittorf, " On Conduction of Electricity in Gases."

You can see the perveance as the digital imprint or the genetic code of the diode because in (1) it constitues the only parameter able to differentiate the multiplicity of the diodes.

Besides the Child-Langmuir's Law is a phenomenological equation, that is derived on physical considerations grounds.

If we use this equation to apply the Least Square Method (LSM) with linear regression to the set of experimental data extracted by the Data-Sheets it is difficult to get a good fitting, as you can see by examining Table 1. In this table S and R represent the Standard Error and the Correlation Coefficient respectively. A perfect fitting is gotten when R is equal to 1. The good values of the Correlation Coefficient R brought in Table 1 must not deceive you, since R is a paramenter of global evaluation and lower values to 0.998 cannot be thought satisfactory as the graphs of the Figg. 1, 2, 3 related to the diodes 12X4, GZ30, GZ33 show, in wich the model introduces, locally, marked deviations. In this graphs the "small black balls" represent the average data extracted from Data-Sheets. In my opinion this model well represent only tubes like 5U4 and GZ40: you can think of them as perfect diodes (although not ideal !). In all the other cases the results can be improved so to get nearest simulations to the reality. The apparent redundance in Table 1 and those following where is present either 12X4 or EZ90/6X4 will be clarified later.

In the "sacred texts" the equation brought for describing the operation of the diode is the well note Child-Langmuir's Law:

Ip= K*Vp1.5   (1);
where:

Ip   is the current that flows in the diode;
Vp   is the anode to cathode voltage;
K   is a costant said perveance.

TUBE	K	S	R
12X4	0.00060995334	0.00138325	0.99735332
5R4	0.00047199449	0.00745654	0.99935083
5U4-GB	0.00077680082	0.00412083	0.99993744
5Y3-GT	0.00027567876	0.00412083	0.99943081
6X5	0.00070088124	0.00313027	0.99958472
EZ80	0.00072196624	0.00168633	0.99948388
EZ81	0.00173282240	0.00510847	0.99878696
EZ90	0.00071166200	0.00203476	0.99960836
GZ30	0.00154941050	0.00610246	0.99817439
GZ33	0.00354419120	0.00587247	0.99674313
GZ34	0.00405103390	0.01029596	0.99915061
GZ37	0.00075322616	0.01065039	0.99840240
GZ40	0.00051502547	0.00055000	0.99993004
GZ41	0.00070531064	0.00127131	0.99917713

Tab. 1;   Results for the $Ip=k*(Vp)^{1.5}$ model

If a direct current electric arc of some length is formed between carbon electrodes, and if a third carbon electrode is so placed as just to dip into the flame of the arc, or if the arc is deflected against it by a magnet, it will be found that a galvanometer or ammeter connected between the positive carbon and the third or lateral carbon indicates a current which may even be strong enough to ring an electric bell. If, however, the ammeter or bell is connected between the negative carbon of the arc and the middle carbon, then no current passes (see Fig. 14).

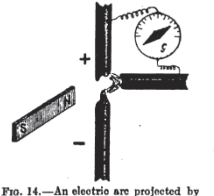


FIG. 14.—An electric arc projected by means of a magnet against a third carbon to show the "Edison effect" in the case of an electric arc.

Also, it can be shown by the same means that the space between the negative carbon of the arc and the middle carbon possesses a unilateral conductivity and will permit negative electricity from a battery to pass from this negative carbon to the middle carbon, but not in the opposite direction (see Fig. 15).

Finally, the author discovered that the same phenomenon can be demonstrated in the air at ordinary pressure. For if a thick carbon filament is rendered incandescent in air by passing a strong current through it, and if an insulated metal plate is held near to it, a galvanometer joined in between this metal

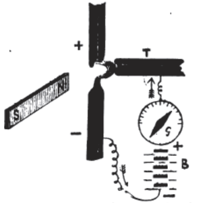


FIG. 15.—An experiment with the electric arc having a third carbon to show that a current of negative electricity can pass under low E.M.F. between the negative terminal of the arc and the third carbon electrode.

plate and the positive terminal of the carbon indicates a small current, but no current if joined in between the middle plate and the negative terminal of the carbon loop (see Fig. 16).

These same effects were the subject of a more extended investigation by the author, the results of which were communicated to the Physical Society of London in 1896, entitled, "A Further Examination of the Edison Effect in Glow Lamps."[1] In this research quantitative measurements were given showing the relation between the Edison effect current—that is, the current through a galvanometer connected between the collecting plate and the positive terminal of the lamp filament and the working voltage of the lamp or potential difference of the ends of the filament.

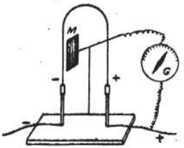


FIG. 16.—An experiment showing the "Edison effect" with a carbon filament rendered incandescent in the open air.

The curve delineating this ratio rises very steeply as the P.D. on the terminals of the filament (called the lamp voltage) increases (see Fig. 17).

The table below gives the results of one set of measurements which are represented graphically in Fig. 17 :

Lamp Voltage.	Thermionic Current in Milliamperes.	Lamp Voltage.	Thermionic Current in Milliamperes.
30	0·085	38	2·36
32	0·190	39	2·71
33	0·44	40	2·99
34	0·84	41	3·37
35	1·23	42	3·71
36	1·69	43	3·99
37	2·01	44	4·25

The galvanometer used to measure the current had a resistance of 6,372 ohms.

It will be seen that the thermionic current through

[1] See *Philosophical Magazine*, July, 1896; also *Proc. Phys. Soc. Lond.*, vol. xiv., p. 187, 1896.

Vacuum diode Models & PSpice Simulations

Stefano Perugini
http://digilander.iol.it/paeng/vacuum_diode_models.htm

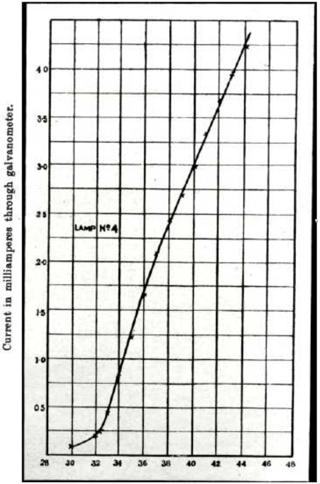
This article appeared originally in Glass Audio, Vol.10,Nr. 4, 1998.

The renewed interest in the thermionic technology applied to the audio is pushing the most sensitive designers to use, widely, the modern tools of circuit simulation SPICE-oriented, in the convincement that the best sonic results to be gotten with a deep circuit optimization and not simply making use of the most expensive component. An ulterior big advantage is given by the facility wich is possible to experiment unusual and effective solutions saving up time and money contemporarily.

In this article I focus the attention in the creation of a very simple but accurate vacuum diode model in the conviction that the correct realization of an audio amplifier cannot be separated from the correct realization of associate power-supply. Moreover many people are convinced that the best sonic results could be gotten just turning to the vacuum diode as rectifier element. Nevertheless the use of such devices presents some problems; in fact it is necessary to check by calculations often dull and not very careful, several parameters as the repetitive peak current, the hot-switching current, the maximum inverse voltage and so on, otherwise it is possible to lead the device to a premature death. On the contrary if you resort to the circuit simulation, on the condition that you have accurate models, you can overcome the optimization phase in the virtual world, totally, and go out only to effect the inevitable micro-adaptations and therefore build the real object.
At the end of this article I will show the goodness of the mathematical model used by comparing it with a real situation, that is comparing the results gotten by measurements on a simple power supply phisically realized, with the results gotten by the same simulated power supply.

START

the galvanometer, when connected between the collecting plate and the positive terminal of the filament, rises to several milliamperes in value. If the galvanometer is



Working volts of lamp.

FIG. 17.

connected between the collecting plate and the negative terminal only a very small current of, perhaps, less than

·001 of a milliampere is found in the case of carbon filament lamps, but this current increases rapidly as the lamp voltage is raised just as does the thermionic current between the collecting plate and the positive lamp terminal. One very curious fact was soon discovered—viz., that the thermionic current may jump suddenly from one value to a much higher one, even though the lamp voltage or P.D. of ends of the filament is kept perfectly constant.

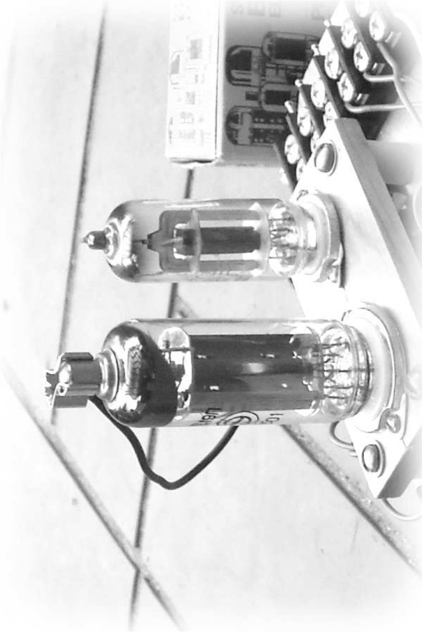
This is shown by the curve in Fig. 18, which delineates the result of one set of measurements of the thermionic current of a carbon filament lamp, with horseshoe-shaped filament, and collecting plate placed midway between the legs, as in Fig. 3.

Another set of observations were made with an electrostatic voltmeter which had its terminals connected respectively to the collecting plate and to the positive terminal of the lamp. It was found in all cases, when the filament of carbon was brought to full incandescence corresponding to 3·5 watts per candle-power, that the metal collecting plate was brought down to the potential of the negative terminal of the lamp so that the P.D. between the collecting plate and positive terminal of the filament was the same, or nearly the same, as the working voltage on the filament. Later observations made with lamps with tungsten wire filaments showed that the collecting plate may even be of rather lower potential than the negative terminal of the lamp, and hence a galvanometer joined in between the collecting plate and the negative lamp terminal may indicate in these cases a certain small current.

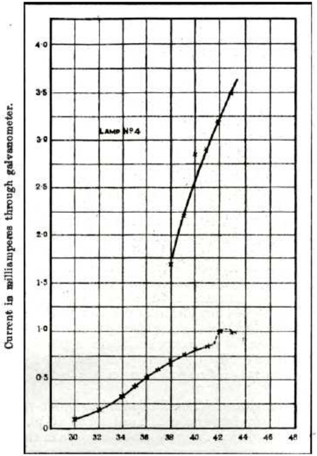
Finally, the author tried some experiments with a vacuum incandescent lamp having a filament made of platinum wire, and proved that the same effects exist as in the case of a carbon filament, though less in degree. The result of all the research work, therefore, conducted on this matter between 1883 and 1896 had made it perfectly clear that in the case of a carbon filament glow lamp, and also of an incandescent metallic wire, there is a projection of atoms, or molecules, from the incandescent filament, and also a projection of negative electricity as well.

4. Before considering the explanation which modern electrical theory gives of the above-mentioned facts with

Photo of the test setup holding the tubes under test.



regard to the incandescent lamp, we must briefly review certain earlier researches in connection with the loss of electricity from incandescent bodies.



Working Volts of Lamp.

FIG. 18.

It had become known to the investigators of electrical phenomena in the middle of the eighteenth century that heat and flame cause a leakage of electricity from charged conductors.

In more modern times Becquerel discovered in 1853 that air at a temperature of about 1500° C. would conduct electricity even under an E.M.F. of a very few volts, and this was confirmed by Blondlot in 1881 and 1887.

An important discovery was, however, made by F. Guthrie in 1873.[1] He first found that at a *red* heat an insulated iron ball could retain a charge of negative electricity but not a charge of positive.

At a *white* heat it could retain neither a positive nor a negative charge.

From certain measurements given by him we may roughly estimate that at temperatures between about 750° C. and 1000° C. an iron ball rapidly loses a charge of positive electricity, and at 1200° C. or 1300° C. and above it immediately loses either a positive or negative charge. Guthrie also showed that a platinum wire spiral heated to a dull red heat by an electric current rapidly discharged a gold leaf electroscope which had been given a negative charge when held near it. If the said platinum wire was heated white hot it discharged the electroscope whether the latter was charged positively or negatively.

The same experiment can be carried out with an iron poker the tip of which is heated to a very bright red heat in a blacksmith's forge. The red hot poker discharges immediately a gold leaf electroscope which has received a negative charge of electricity, but does not discharge it if it has received a positive charge, when held near to it.

These researches were continued about the year 1880 on rather different lines by Elster and Geitel, and their method consisted in heating by an electric current either a metallic wire or a carbon filament included in a glass vessel which could be exhausted or filled with different gases. Near this heated filament was fixed a metal plate carried on a wire sealed through the glass (see Fig. 19). This plate was connected to an electroscope. It was found that the plate became charged to a certain potential when the wire was heated.

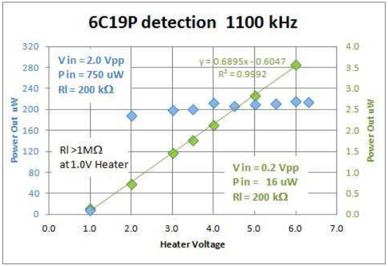
Generally speaking, it was found by Elster and Geitel that a metallic wire gave off positive electricity at a temperature near or below a red heat, but at higher temperatures it evolved negative electricity, which increased rapidly in

[1] See *Phil. Mag.*, 4th Series, vol. xlvi., p. 257, 1873, "On a Relation between Heat and Static Electricity."

at 20mV input (2.0Vpp on signal generator), and a monotonic increase in output power at 6mV input (0.2Vpp on the generator). I was seeking a peak output power at around 4.0V on the heater so this result is disturbing. I can hear it, but cannot measure it.

Biasing the plate positive will have the effect of "pulling" the space charge towards the plate increasing the current while a negative plate bias will have the opposite effect. With 6.0V heater it will take nearly a negative half volt before the current stops. This is death to sensitivity in a crystal set. Operating the heater at 4.0V provides the most efficient rectification.

Note also that high perveance is not merely a matter of placing the plate as close as possible to the cathode. This may cause an excessive zero-bias current to overcome. The surface-area of both cathode and plate are also critical with large areas providing high current transfer. Vacuum tubes such as pentodes with an included diode plate are poor rectifiers having very low perveance. This is due to the small plate stuck in with all the other hardware in the tube. Get a "fit for purpose" diode for best results.



Note that while the above model as well as hearing (a kind of "hearing is beleiving" thing) supports the 4.0V heater voltage as a sweet spot for highest rectification efficiency, I have as yet not been able to measure this. Using my tube-driven Telefunken set (see description on my main radio page) I made a series of output signal power measurements at various tube heater voltages. I we see no relation between matched output power and the tube heater voltage

quantity as the temperature was raised, and therefore gave a negative charge to the insulated plate. Carbon filaments, however, were found to give off negative electricity at all temperatures.

As some references later on will be made to the published papers of Elster and Geitel we give here the titles (in English) and references to the principal papers which concern us in this subject.

(1) "On the Electricity of Flames," *Wiedemann's Annualen*, vol. xvi., p. 193 (1882).

(2) "On the Generation of Electricity by the Contact of Gases and Incandescent Bodies," *Wied. Ann.*, vol. xix., p. 588 (1883).

(3) "On the Unipolar Conductivity of Heated Gases," *Wied. Ann.*, vol. xxvi., p. 1 (1885).

This paper deals with the unsymmetrical conductivity of flames.

(4) "On the Electrification of Rarefied Gases and Electrically Heated Wires," *Wied. Ann.*, vol. xxxi., p. 109 (1887).

In this paper Elster and Geitel describe experiments made with an exhausted glass bulb having stretched across it a platinum wire which could be heated electrically. Above the wire was a metal plate carried on a platinum wire sealed through the glass (see Fig. 19). The bulb could be exhausted or filled with various gases. There is no mention of the use of a carbon filament.

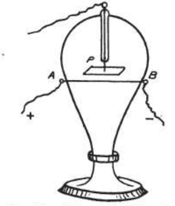


FIG. 19.—Exhausted bulb with incandescent wire, *AB*, in it, and metal plate, *P*, used by Elster and Geitel to show the emission of electricity from incandescent wires.

(5) "On the Generation of Electricity by Contact of Rarefied Gas and Electrically Heated Wires," *Wied. Ann.*, vol. xxxvii., p. 319 (1889).

In this paper (dated March, 1889) Elster and Geitel mention the unilateral conductivity for direct currents of rarefied gases in tubes with one hot and one cold electrode.

They employed for some experiments a carbon filament lamp with a plate sealed into the bulb, and mention that the filament emits negative electricity. There is no mention of the use of such a tube or lamp for rectification of alternating currents.

This last paper of Elster and Geitel was only published a few months before the paper sent (in December, 1889) by the author to the Royal Society, to which reference has already been made.

The work of Elster and Geitel was purely scientific and had no technical application for the rectification of alternating currents or the use for any practical purpose of a carbon filament vacuum lamp having a metal plate sealed into the bulb.

5. One characteristic of all the investigations on this subject, as above mentioned, was that none of their authors had been able to put forward any satisfactory explanation of the facts thus discovered. The ordinary two-fluid or single-fluid theory of electricity and likewise Maxwell's electromagnetic theory failed to give any reasons for these striking differences between the behaviour of positive and negative charges on hot bodies.

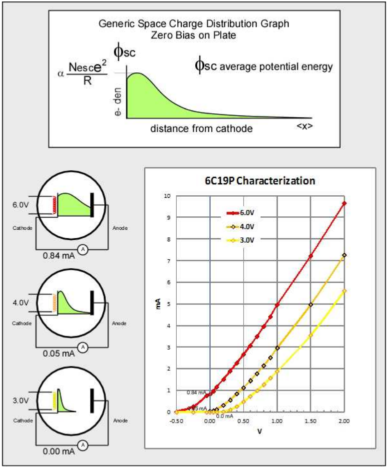
In 1897 Sir J. J. Thomson made the first publication of the remarkable investigations which enabled him to demonstrate that negative electricity is always associated with masses at least 1,800 times smaller than the mass of an atom of hydrogen and that under certain conditions these electric corpuscles are emitted from hot bodies.

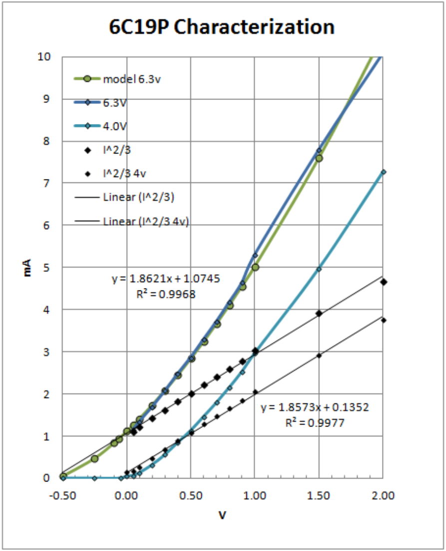
Faraday long ago proved that in the electrolysis of liquid conductors the passage of a certain quantity of electricity through the liquid is always accompanied by the movement to, or liberation upon, the electrodes of a fixed quantity of matter or products of decomposition of the electrolyte.

It was then and after recognised that electricity is conveyed through electrolytes only in association with atoms, or groups of atoms, called *ions*, in a fixed ratio, and that every such ion carries with it an electric charge which is an exact integer multiple of a certain unit charge.

In the case of the hydrogen atom or ion resulting from the passage of electricity through aqueous solutions of salts the quantity of electricity carried by the whole number of atoms of hydrogen which together weigh 1 gram (called the gram-

A conceptual look at the impact of heater temperature on the space charge distribution in the annulus between cathode and anode. I start by drawing a qualitative plot of charge density versus distance from the cathode. This is not how such plots are done in the literature but it is a nice visualization. The distribution of charge is a statistical function of heater temperature and plate bias. For the zero-bias case I show qualitative distributions for three heater voltages, 3.0, 4.0, and 6.0 volts. On my chart of current/voltage I find no current flows with 3.0 volts on the heater. Current just begins to be measurable at 4.0V and at 6.0V I found a significant 0.83mA of current indicating that a good portion of the space charge is not impinging on the plate even with zero bias.





Perveance calculation for the 6C19P diode taken at 6.3 v and 4.0 v heater voltages.

atom of hydrogen) is 96,500 coulombs, or very close to it. Hence, since one coulomb is equal to one-tenth of an electromagnetic unit (E.M.U.) of electrical quantity, we can say that for the hydrogen ion or atom, the weight of which is taken as unity, the ratio of charge (*e*) to mass (*m*) is 9,650.

According to Faraday's Law of Electrolysis the same quantity of electricity passed through various electrolytic cells will liberate on the electrodes masses of ions which are in the ratio of the chemical equivalents of these substances.

Exhaustive experiments have shown that a current of one ampere flowing for one second—that is, one coulomb—deposits in a silver voltameter 0·001118 gram of silver on the cathode. The atomic weight of silver is 108 and its valency is unity. Hence 108 is its chemical equivalent, that of hydrogen being unity. Accordingly a current of one ampere liberates from a water voltameter in one second a mass of hydrogen equal to 0·00001035 gram. In other words, 96,500 coulombs, or 9,650 E.M.U. of electric quantity, liberates one gram of hydrogen and 108 grams of silver at the cathodes of electrolytic cells.

Now 3×10^{10} units of electric quantity in electrostatic measure (E.S.U.) are equivalent to the electromagnetic unit. Accordingly $2895 \times 10^{11} = 3 \times 10^{10} \times 9,650$ E.S.U. will liberate at 0° C. and 760 mm. pressure 11,200 cubic centimetres of hydrogen gas which weighs one gram.

Modern researches on the kinetic theory of gases have shown that in one cubic centimetre of any gas at 0° C. and 760 mm. there are most probably $2{\cdot}7 \times 10^{19}$ molecules. As the molecule of hydrogen contains two atoms there are $11,200 \times 5{\cdot}4 \times 10^{19}$ atoms of H. liberated by the passage of $2,895 \times 10^{11}$ electrostatic units of electricity. Hence each hydrogen ion or atom must be associated with

$$\frac{9,650 \times 3 \times 10^{10}}{11,200 \times 5{\cdot}4 \times 10^{19}} = 4{\cdot}77 \times 10^{-10}$$

electrostatic units (E.S.U.) of electric quantity.

This charge of the hydrogen ion is denoted by *e* and is a negative charge. Hence we have

$$e = 4{\cdot}77 \times 10^{-10} \text{ electrostatic units.}$$
$$= 1{\cdot}59 \times 10^{-20} \text{ electromagnetic units.}$$

This very small quantity of electricity is Nature's unit of electricity and it is the quantity of negative electricity carried by one hydrogen ion in electrolysis. It is therefore a very important unit and was named by Dr. G. Johnstone Stoney in 1891 *an electron*, the importance of such designtion having been indicated by him as early as 1874.[1]

The mass of a hydrogen atom is $1{\cdot}662 \times 10^{-24}$ gram, and therefore the ratio of charge to mass or e/m for the hydrogen ion is 9,650 when e is measured in electromagnetic units.

The study of the phenomena of electrolysis had already convinced some physicists that electricity, like matter, most probably exists in small indivisible units which may be called *atoms of electricity*. The charge of the hydrogen ion is this electric atom or electron, and all ions carry this unit or else some exact integer multiple of it in electrolysis.

6. Meanwhile evidence had been accumulating that in the case of conduction through gases electricity was moved in association with masses or matter of some kind.

The discharge or conduction of electricity through the very rarefied gas in a high vacuum had been shown by Sir William Crookes to be accompanied by the projection of particles from the cathode or negative terminal which had all the properties of material particles in motion. When they impinged on small paddle wheels mounted in the vacuum tube they caused these wheels to rotate and they also produced intense phosphorescence when falling upon certain substances, whilst other solid bodies placed in the path of the discharge cast shadows in their wake.

These particles also behaved as if they carried charges of negative electricity, being deflected by magnetic or electric fields.

Approaching these known effects from a new point of view, Sir J. J. Thomson devised experimental methods of extraordinary ingenuity and power which enabled him to measure the ratio of charge to mass in the case of these cathode ray particles in a high vacuum tube.

It will not be necessary to describe these methods in detail because the reader can obtain all information about them either from Thomson's book, *Conduction of Electricity through Gases* (see chap. v.), or from any advanced text-book on modern physics. Suffice it to say that the method depends upon the deflection of a cathode ray particle from

[1] See *Transactions of the Royal Society of Dublin*, vol. l., p. 582, 1891; also *Phil. Mag.*, 1881, p. 385.

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6C19P measurements and 6.3 and 4.0 v heater voltage:

V in	I 6.3	I^2/3	I calc		I 4.0	I^2/3	I calc
-0.57			0.00				
-0.55			0.01				
-0.50			0.06				
-0.25			0.48				
-0.10			0.84				
-0.06			0.95				0.00
0.00			1.11		0.05	0.14	0.05
0.05	1.15	1.10	1.26		0.06	0.16	0.11
0.10	1.34	1.22	1.42		0.13	0.26	0.18
0.20	1.69	1.42	1.74		0.32	0.47	0.36
0.30	2.07	1.62	2.09		0.56	0.68	0.58
0.40	2.48	1.83	2.45		0.85	0.90	0.82
0.50	2.86	2.01	2.84		1.13	1.08	1.10
0.60	3.29	2.21	3.24		1.46	1.29	1.40
0.70	3.71	2.40	3.66		1.79	1.47	1.72
0.80	4.17	2.59	4.10		2.15	1.67	2.06
0.90	4.64	2.78	4.56		2.53	1.86	2.43
1.00	5.30	3.04	5.03		2.97	2.07	2.81
1.50	7.79	3.93	7.60		4.98	2.92	4.99
2.00	10.08	4.67	10.50		7.27	3.75	7.55
Perveance =		2.54				2.53	
calc							
I = (1.862V + 1.075)^3/2					I = (1.857V + 0.135)^3/2		

Spreadsheet for calculation of diode Rd

Diode Tub	P	Rdc	V = 0.2
under test		Ohm	
6C19P	2.540	0.59	
5726	2.190	0.68	
6DN3	5.400	0.28	
20D1	2.020	0.74	
5C12P	0.320	4.66	
1S5	0.063	23.66	
2D1S	0.155	9.62	
6G2	0.050	29.81	
6AL5	2.420	0.62	
6H6	0.500	2.98	
7Y4	0.580	2.57	
2X2A	0.017	87.69	
6V3-A	2.300	0.65	
6AX4GT	1.420	1.05	
6AV6	0.085	17.54	
1A3	0.075	19.88	
	1.258	1.3E+01	
mA ^ 2/3 = 1.86 * V + 1.07			
Langmuit-Child		I = PV^3/2	
Instantenous Resistance			
	dV/dI = 1/(1.5P*sqrt(V)) = 2/3 * 1/P * 1/sqrt(V)		

its path by the simultaneous action of an electric field and a magnetic field at right angles to each other and to the direction of motion of the particle (see Fig. 20). The charge carried by the cathode particle is denoted by e and its mass by m and the experiments give the ratio e/m where e is measured usually in electromagnetic units. A brief outline of the theory of the action as given by Sir J. J. Thomson is as follows:

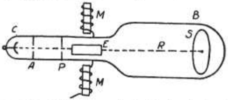


FIG. 20.—Cathode ray tube, having internal deflecting plates, E, and external deflecting magnets, M, and phosphorescent screen, S, to show the deflection of cathode rays by electric or magnetic force.

Let a particle of mass m, carrying a charge of electricity e, be moving in a straight line with velocity v, and let a magnetic force H act on it at right angles to its line of motion. Let e be in electrostatic units and H in electromagnetic units. Then the mechanical force acting on the particle is μHev, where μ is the magnetic permeability of the medium. Hence if we take the dielectric constant K of the medium to be unity, since $\mu K=1/c^2$ where $c=3\times10^{10}$, we have the force f acting on the particle given by Hev/c^2 and the acceleration$=Hev/mc^2$ and the space moved over in a transverse direction in a time t is $\frac{1}{2}\frac{Hev}{mc^2}t^2$.

Let this displacement be called δ. Then during the same time the particle moves a distance l in the original direction, where $l=vt$. Hence $\delta=\frac{1}{2}\frac{Hev}{mc^2}\frac{l^2}{v^2}=\frac{1}{2}\frac{l^2}{c^2}H\frac{e}{m}\frac{1}{v}$. Now δ, l and H are capable of measurement, and hence $\frac{e}{m}\frac{1}{v}=A$, say, becomes known.

Again, suppose we subject the particle to the action in a transverse direction of an electric force E at right angles to its line of motion. The mechanical force exerted on it is Ee and its acceleration is eE/m and its displacement in a time t is

$$\delta^1=\frac{1}{2}\frac{eE}{m}\left(\frac{l}{v}\right)^2=\frac{E}{2}l^2\frac{e}{m}\frac{1}{v^2}.$$

Hence, if δ^1, l and E are measured, we obtain $\frac{e}{m} \cdot \frac{1}{v^2} = B$, say,

If then we adjust matters so that the two displacements δ and δ^1 are equal and observe E, H and l we have $v = A/B = c^2 \frac{E}{H}$ and $\frac{e}{m} = 2 \frac{c^4}{l^2} \cdot \frac{E}{H^2} \delta$.

If the particle carrying the charge is a cathode ray particle then we can observe the deflections due to the electric and magnetic forces by allowing the particle to strike against a screen covered with phosphorescent material and there causing the appearance of a bright spot of light. The displacement of this spot enables us to measure δ and δ^1. The details of the apparatus required for this purpose will be found described in Thomson's book *Conduction of Electricity Through Gases*, chap. v., or in his book *The Corpuscular Theory of Matter* (Constable & Co.).

Thomson's most important experimental result was that the ratio e/m was quite independent of the nature of the residual gas in the high vacuum tube and of the material of which the cathode was made. His early numerical measurements were found subsequently to be rather too low, but the measurements being repeated by him and many other physicists have led to the conclusion that for the cathode ray particle the ratio e/m is very nearly $1{\cdot}77 \times 10^7$ when e is measured in electromagnetic units, and is $5{\cdot}31 \times 10^{17}$ if e is measured in electrostatic units.

Now this number, $1{\cdot}77 \times 10^7$, is at once seen to be more than 1,700 times greater than the ratio $e/m = 9{,}650$ for a hydrogen ion, and the question at once arose, is this due to e being greater or m being less in the case of the cathode particle? To settle this question, Thomson devised other experiments of very great ingenuity, based on the following principles :

If air at ordinary temperature and pressure is saturated with moisture any sudden expansion or enlargement of the vessel containing it, which increases the volume in a ratio of about 5 to 4, will not cause any cloudiness to appear in the vessel, provided the air is quite free from dust. Dust particles act as nuclei for condensation of water-vapour into water particles forming clouds. Hence dust free from air may be cooled by expansion to a certain degree, and

Here you see the impact of lower operating voltages. With the tube operating between 3 and 4 volts the characteristic curves begin to pass through the origin as in regular solid-state diodes and crystals. It is precisely in this voltage range that I found the radio sensitivity, as measured by loudness to my ear, to be most pronounced. It appears that the diode characteristic needs to pass through the origin of the I-V graph for highest sensitivity. This takes me to the 20D1 tube which operates at 9v but only 200mA. This will still take a power supply to use, but the good thing is that the characteristic curve passes through the origin. Running at its design parameters the tube looks a lot like the 6C19P at 4v.

Note on Perveance

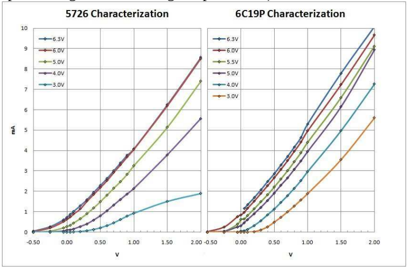
Just a few charts and spreadsheets on my calculations for diode valve perveance. I was very impressed at just how accurately the Langmuir-Child relation was able to predict the modeled results. This enabled me to reduce the observed data to a simple equation that shows the characteristic of the diode over a wide range of voltage values.

My attempts at calculating the diode resistance proves more troublesome. I can easily calculate the diode DC resistance which is low over the operating ranges. The AC resistance will wait until I know more. Stay tuned!

6AX4GT	1.42
6AV6	0.085
1A3	0.075

The high-perveance diode tube types I tested show an interesting property in that their characteristic curves do not pass through the origin of the graph. These curves are wholly acceptable as crystal radio detectors although they will require power to operate. What I have noticed with such tubes is that when I turn them off after using them with a radio, on cooling they go through a period of much increased sensitivity (very loud) before fading to nothing. It is as though running them at the full 6.3V lowers their full potential as crystal radio rectifiers. The reason is in the high perveance of the tubes, the anode is already proximate to the space charge before any plate voltage is applied. Effectively, while the plate (anode) "Zero" voltage is measured with respect to ground, the plate itself is still positive with respect to the cathodic space charge. Small currents will continue to flow even with a negative bias to the plate, (Contact potential).

In order to explore this idea, I ran a series of tests with the tubes running at lower operating voltages (effectively diminishing the space charge thus lowering the perveance) as shown:



will remain supersaturated with water-vapours uncondensed into cloud.

It was, however, shown by C. T. R. Wilson, in 1897, that gaseous ions in air—that is, atoms or groups of atoms having a positive or negative electric charge—could act like dust particles and cause precipitation of water vapour into white clouds, when the air was suddenly increased in volume in the ratio of not less than 4 to 5, or by about 20 to 25 per cent. It had also been found that Röntgen or X-rays could create gaseous ions in air, and these, like dust particles, have the property of condensing water vapour round them so as to form a cloud of water spherules, when air supersaturated with water and containing gaseous ions is suddenly expanded in volume in about the ratio 5 to 4.

7. J. J. Thomson applied this discovery of C. T. R. Wilson in a highly-remarkable way to determine the electric charge on a gaseous ion produced by the action of X-rays or any other means.

A glass vessel has in it a tightly-fitting piston which can be suddenly displaced so as to expand some air saturated with water vapour. If this air is dust-free and expanded to not more than 1·25 times its original volume, no cloud will be formed.

If the air is ionised by exposing it to Röntgen or X-rays, some of the air molecules will acquire a positive and some a negative charge. These act as nuclei and condense round them water molecules, so that when the air is expanded suddenly a cloud forms in the vessel. If the expansion ratio is between 1·25 and 1·3 only negative ions are caught, and condense water vapour molecules round them. If this cloud is left to itself it subsides in the vessel, because each little droplet of water very slowly falls through the air.

If the radius of each spherical droplet of water is a, and if c is the coefficient of viscosity of the air, then the drop in falling soon attains a final constant velocity, v, which Sir George Stokes had previously proved was given by $v=\frac{2}{9}\frac{a^2}{c}g$, where g is the acceleration of gravity.

The proof of Stokes's formula is rather long, but it is given in Lamb's treatise on *The Motion of Fluids* (chap. ix.,

p. 226), and also in Stokes's original paper in the *Cambridge Philosophical Society's Transactions*, vol. ix., p. 48. Stokes showed that the falling sphere is losing potential energy at a rate $6\pi acv^2$, and hence the moving force is $6\pi acv$. But this must also be equal to $\frac{4}{3}\pi a^3 g(\sigma-\rho)$, where σ is the density of the sphere and ρ that of the medium. In the case of a water sphere falling in air, ρ is negligible compared with σ. Hence we have $v=\frac{2}{9}\frac{a^2 g}{c}$.

Accordingly, when the cloud of vapour sinks, we can observe the rate at which the upper surface, which is well defined, falls, and this gives us the value of v.

Maxwell found that the viscosity (c) of air, not very highly rarified, is independent of the density, but proportional to the absolute temperature, and for air at t° the value of c is

$$c=0{\cdot}0001878\,(1\times 0{\cdot}00366\,t^\circ).$$

A drop of rain of $\frac{1}{1000}$th inch in diameter, therefore, falls at the rate of only $\frac{3}{4}$ inch per second in still air. This explains how it is that the white clouds of water particles seen in the sky appear to float in the air. They are in fact falling to earth but very slowly.

If, then, in the Thomson experiment there are n negative ions in each cubic centimetre and each forms the nucleus of a spherical drop of water cloud of radius a, the whole volume of water per c.c. is $q=n\frac{4}{3}\pi a^3$.

Let ρ_1 be the density of the water vapour after expansion, but before condensation begins, and ρ the density at the final temperature t°, then $\rho_1-\rho=q$. If L is the latent heat of water vapour, then Lq is the heat given out in this condensation. During the sudden expansion the air will be cooled from $T^\circ C$ to t°_2C., but the evolution of the latent heat by condensation raises the air to a temperature, t°. If S is the specific heat of air and M the mass per unit volume, we have

$$Lq=SM\,(t-t_2).$$

Hence $$\rho=\rho_1-\frac{SM}{L}\,(t-t_2).$$

In this equation ρ is a known function of the temperature, t, and this is given in hygrometric tables. If T is the

A question remains as to what in fact is different about these tubes to give such different characteristics. While the I/V characteristic of most vacuum diodes pretty much follow the Langmuir-Child Law, the steepness of the I/V characteristic is largely due to the geometry of the tube elements and the volume of electron space-charge between them. JB Calvert's Theory of Vacuum Tubes informs one that this is the property called Perveance in a vacuum diode. Measuring this requires plotting I raised to the 2/3 power against V and taking the slope of the best-fit line through the data. This slope raised to the 3/2 power is the perveance. With my measurements this was practical and quickly done, results as follows:

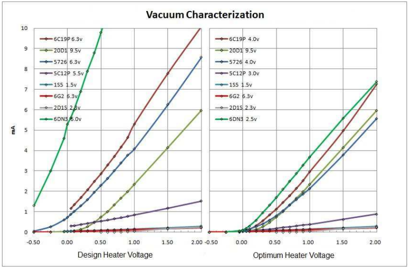
Tube	Perveance	R2	
6C19P	2.54	0.997	
5726	2.19	0.998	
6DN3	5.40	0.997	
20D1	2.02	0.985	(Langmuir-Child?)
5C12P	0.32	0.999	
1S5	0.063	0.999	
2D1S	0.155	0.975	(Langmuir-Child?)
6G2	0.050	0.999	

The perveance numbers above range from 0.02 to over 2 mA/V^3/2 (with >2 being good for small-signal detection) and clearly shows my choice of the 6C19P to be an excellent one. I am surprised to see a huge 5.4 for the 6DN3 diode, a color television damping diode. It takes a Novar 9-pin socket and is a large tube so doing more with this tube may have to wait a bit.

Calvert's 2001 published data

Tube	Perveance
6AL5	2.42
6H6	0.50
7Y4	0.58
2X2A	0.017
6V3-A	2.3

comparison. I was hoping to find a good candidate with sensitive characteristics and low energy consumption. As you will find, such a beast did not exist. Following this research began a period of purchase and testing.



I have finally found, purchased and tested eight different tube types (plot above) including 6.3V rectifier diodes that take a lot of power to run and are not really suitable for battery use, a 9v dual diode tube (20D1), a pentode/diode tube (1S5) that is designed to run on a battery at 1.5V and 50mA, and a couple miscellaneous but cute tubes. In testing the 1S5, I found the filament never glowed incandescent at 1.5V and, on measuring, was barely sensitive to anything. I cannot imagine this tube would make much of a diode for crystal radio use. I tested different manufacture 1S5 tubes from two different suppliers. No dice. Finally, I tried to push the tube to operate at higher-than-specified voltages. At 4.3V the I-V curve was still very flat, but shifted slightly higher, crossing the Amp axis at about 0.4 mA, (see graph). At 5.5V one of my tubes gave up the ghost and I didnt do more. I pretty much rule the 1S5 out for my crystal radio work. Looks like i'll be needing the power supply when I get around to building/operating that Fleming Radio.

temperature at the beginning of the experiment, and P the pressure of the gas in millimetres of mercury, then since 1 c.c. of air at 0^0C and 760 m.m. weighs 0·00129 gram, we have

$$M=\frac{\cdot 00129}{x}\cdot\frac{273}{273+T}\cdot\frac{P}{760},$$

where x is the ratio of final to the initial volume of the gas.

Also, $$\rho_1=\frac{\rho^1}{x}$$

where ρ^1 is the density of water vapour at T^0C before expansion. This can be obtained from the hygrometric tables.

Now, in adiabatic or sudden expansion of air the relation between volume v and pressure p is given by the equation $pv^{1\cdot 41}=a$ *constant*; whilst for slow expansion we have $pv=R\theta$, where R is the so-called gas constant, and θ is the absolute temperature. Therefore, for adiabatic expansion,

$$v^{0\cdot 41}\times\theta=a\ constant$$

or $$\log_e\frac{\theta_1}{\theta_2}=0\cdot 41\log\frac{v_1}{v_2}$$

or $$\log_e\frac{273+T}{273+t_2}=0\cdot 41\log x.$$

From this equation we can find t_2, when x and T are given. Then we have:

$$\rho=\frac{\rho^1}{x}-\frac{SM}{L}(t-t_2)$$

and we can substitute the value of t_2 and x from the previous equation. This last equation can be solved by substituting various values for t, and finding the corresponding value of ρ, until we reach values of t and ρ, which agree with the corresponding values in the hygrometric tables.

Having then found ρ and ρ_1 we know q, and also having found a from Stokes formula we find $n=3q/4\pi a^3$, which gives us the number of drops and therefore of negative ions in the cloud.

By this very ingenious method Thomson weighed the cloud of water spherules and counted the drops of water forming the cloud and therefore determined the number of ions round which the drops were formed. He had then to

RADIOTELEGRAPHY AND TELEPHONY

determine the whole electric charge contained in this miniature thundercloud. To do this the cloud was formed between a metal plate connected to one terminal of an electrometer, the other terminal being joined to the water surface which supplied the water vapour. If the electrometer is charged to a potential difference V and if the capacity of the whole system is C, then $\frac{Cdv}{dt}$ denotes the rate at which electricity is lost or gained by each terminal.

When so placed between two surfaces at potential difference V and distance apart d the ions are subject to an electric force $E=V/d$, and if A is the area of the plate and u the velocity of the ions per unit potential gradient or electric force, then $neuEA$ is a measure of the electric current represented by the slow migration of all the ions under the action of this electric force E.

Sir E. Rutherford had determined the velocity of a negative ion in air at normal pressure to be 1·5 centimetres per second per potential gradient of 1 volt per centimetre.

Hence in electrostatic units $u=1{\cdot}5 \times 300=450$.

Accordingly if we determine the loss of electricity per second corresponding to a certain reduction in deflection of the electrometer and so find the value of the decrease expressed as a current in electrostatic units, we have the value of $neuAE$, and hence of e the ionic charge, when all the other quantities are known.

In this way Thomson first found a value for e the electric charge in a hydrogen ion to be $e=6{\cdot}5 \times 10^{-10}$ electrostatic units. But subsequent measurements by Thomson and others, and especially recent work by Prof. R. A. Millikan, have given a corrected value $e=4{\cdot}774 \times 10^{-10}$ (E.S.U.).

The above-described experiment repeated with various moisture-saturated gases ionised in various ways, by Röntgen rays or by radium, always gave the above value for the ionic negative charge e, and it will be seen that it is exactly the same as the charge of the hydrogen ion obtained from electrolysis of aqueous solutions.

Hence it is more than probable that we are here concerned in all cases with the same natural unit of electricity—viz., the electron.

We have, however, seen that in the cathode ray tube the ratio of e/m for the cathode ray particle is $5{\cdot}31 \times 10^{17}$, when

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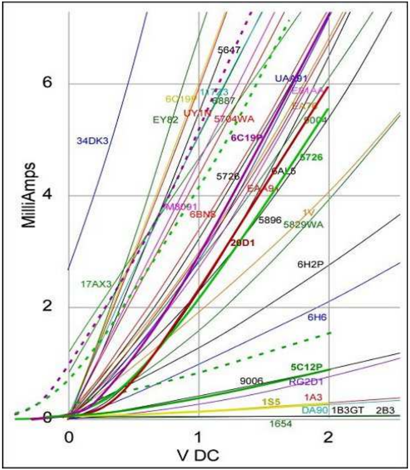
Vacuum Diodes



When I decided early on to construct a radio based on the vacuum diode (see my Fleming Radio section), I had to find a suitable tube for the project. That began with an extensive search through the datasheets checking vacuum diode properties and reviewing the characteristic curves for a large number of diode tubes. Datasheet characteristic curves, if they exist at all, are notoriously difficult to make comparisons between. In the above figure I plot as best I can the V/I characteristics at low signal levels on a common plot for units with the same features. Still, the supply regulator was never designed to adjust the output to precise small values making it somewhat difficult/tedious to adjust. Adding a small rheostat to the test jig may aid for making fine adjustments on the voltage. Another piece of equipment you will need for this test is an amp meter. I use a nice small digital meter I found new on ebay for $15 shipping included. It reads amps to a lowest range of 200uA, more than enough precision for the task. For that price get two. The DVM is, of course, my trusty Keithley workhorse. Easy protocol as follows:

1) Set up the test with the diode and meters clipped to the jig.

2) Adjust the power supply until the reading on the DVM meter is where you plan to measure. Adjust the voltage (DVM readout) in steps from 0 to 1.0 Volt in 0.1 V increments and record the current (Amps) in a spreadsheet.

3) Repeat at each tenth volt recording while the spreadsheet makes a sweet graph.

Test Results

First, I offer a quick look at my diode modeling setup. I am currently upping the ante on resolution in order to determine diode parameters Is and n, hoping for success soon! Setup and protocol..

Over a period of a few weeks I ran I-V characterization tests on a good number and variety of diodes, crystals and my two tubes to see how very thing stacks up. The following presents the resulting curves, diode photos, and some puzzling questions/conclusions I churned up in the process. I start off with the realization that when one orders diodes, it is by no means certain what one will get. This seems especially true for the supposedly ubiquitous 1N34A. Unless you see the part number actually on the diode, you probably need to test it to know what it really is. So, lets take a look!

e is reckoned in electrostatic units, and accordingly the mass m of the cathode ray particle must be

$$\frac{4{\cdot}77\times10^{-10}}{5{\cdot}31\times10^{17}}=9\times10^{-28}\ \text{gram}=m.$$

But we have seen that there are most probably in 1 c.c. of hydrogen at 0° C. and 760 mm. $2{\cdot}7\times10^{19}$ molecules or $5{\cdot}4\times10^{19}$ atoms, and this volume of gas weighs 1/11,200 gram. Hence the weight of an atom of hydrogen is $1{\cdot}66\times10^{-24}$ gram. Therefore the cathode ray particle has a mass which is 54/100,000, or about $\frac{1}{1850}$th of that of a hydrogen atom.

This astonishing experimental achievement of Sir J. J. Thomson revealed therefore that in these cathode ray particles or corpuscles we have masses nearly 2,000 times smaller in mass than atoms of hydrogen, up until then supposed to be the smallest masses in Nature.

8. Sir J. J. Thomson then directed his attention to two other cases in which electricity passes through gases, one of which particularly concerns us here.

If an insulated plate of zinc is charged with negative electricity and is illuminated by ultra-violet light the charge rapidly leaks away to an earth-connected grid or grating placed parallel in front of the zinc plate. Electricity must therefore pass through the air from one surface to the other.

Suppose then that we have two metal plates placed parallel to each other and that we bring them to different potentials. There is then an electric force acting in the space normal to the plate surfaces. If a uniform magnetic field of strength H is created with its lines parallel to the plate surface we shall have electric and magnetic forces perpendicular and parallel respectively to the metal surfaces.

Let an ion start from one of the plates which we shall suppose to be the negative plate and move towards the other positively charged plate under the action of the electric force E. Let d be the distance between the plates, and let them be at a difference of potential V; then $E=V/d$. Let H be the magnetic force parallel to the plates and let e be the ionic charge. Then Ee is the mechanical force on the ion perpendicular to the plates. The ion, however, experiences a deflecting force equal to the product of He and its velocity at that instant and perpendicular to the direction of that velocity.

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Suppose that the place from which the ion starts is taken as the origin and that the axis of x is taken perpendicular to the plates and that of y parallel to the plates. Then dx/dt and dy/dt are the axial component velocities of the ion.

The resultant force on the ion along the x-axis is then $Ee-He\frac{dy}{dt}$, and that along the y-axis is $He\frac{dx}{dt}$. Accordingly by the Second Law of Motion we have the equations

$$m\frac{d^2x}{dt^2}=Ee-He\frac{dy}{dt}$$

$$m\frac{d^2y}{dt^2}=He\frac{dx}{dt}$$

or using the Newtonian notation in which a dot over a letter signifies differentiation with regard to time, and two dots double differentiation, we have the equations,

$$\ddot{x}=E\frac{e}{m}-H\frac{e}{m}\dot{y}$$

$$\ddot{y}=H\frac{e}{m}\dot{x}$$

These equations show that the path of the ion is a cycloid.

A cycloid is the curve described by a point on the circumference of a circle which rolls on a straight line.

Let OPQ be a circle (see Fig. 21) rolling on a straight line OA. Let P be any point on the circle, and let the radius of the circle $OC=r$. Let x and y be the co-ordinates of P, and A the origin or contact place from which the circle starts to roll.

Then let $AN=y$ and $NP=x$, and let the angle through which the circle has turned $=OCP$ be denoted by pt, where p is angular velocity, and t=time of rolling. It is then obvious that

$$x=r-r\cos pt$$
$$y=rpt-r\sin pt$$

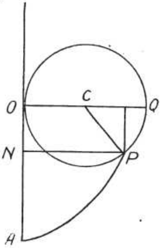


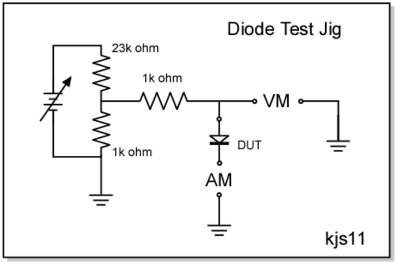
FIG. 21.—Generation of a Cycloid.

Diode Testing

Kevin Smith

http://www.lessmiths.com/~kjsmith/crystal/dtest.shtml

So, what is the best diode out there to use? Do crystals always show poor sensitivity compared to germanium? What about Fleming's marvelous device, the vacuum diode? I start by using a test jig, the design shamelessly modified from Dan Petersen in the Nov 2009 Crystal Set Society Newsletter, (if you aren't a member, go sign up to be.. NOW):



This is a very simple circuit allowing power input, attaching a diode for testing, and sampling both the curent and voltage across the diode under test, (DUT). I made a simple modification by adding a voltage divider, about 20:1 at the power input. The power supply can be connected either at the front across the divider, or after the divider in front of the 100k current limiting resistor for higher voltage readings. I get the input voltage from a modest 18V, 2A regulated DC power supply. This unit has both volt and amp controls with digital readouts, nice to use and dosnt take up much room on my desk. Here is a case where I recommend you look at getting a new unit. I looked long and hard on ebay, but found few bargins and few

Differentiate these equations twice with regard to t, and we obtain

$$\ddot{x}=rp^2-p\dot{y}, \quad \ddot{y}=p\dot{x}.$$

If we compare these two last equations with the above equations of motion of the ion, we see at once they are identical provided we put $p=H\frac{e}{m}$ and $r=\frac{E}{H^2}\frac{m}{e}$. This proves that the path of the ion must be a cycloid.

Hence, if the ion starts from one plate under the action of the two forces due to the electric and magnetic force, it will curl round in a cycloidal path. If, then, the distance between the two plates exceeds twice the radius of the circle, or $\frac{2E}{H^2}\frac{m}{e}$, the particle will never reach the second plate.

Thomson applied the above theorem to the case of the ions emitted by an incandescent carbon filament. He stretched a filament close in front of a metal plate, and placed at a certain distance, d, from it a second parallel metal plate. These plates and filaments were included in a glass vessel very highly exhausted. The filament was connected to the plate just in contact with it, and a difference of potential, V, made between the plates.

Hence the electric force $E=V/d$. Coils of. wire were placed outside the tube, and through them a current was sent, so as to make a magnetic force, H, of known and adjustable value parallel to the plates. When the carbon filament was made incandescent it emits, as we have seen, negative ions, and by adjusting the magnetic field it was possible just to prevent these ions reaching the second plate. From measurements of H, V, and d it was then possible to solve the equation $d=\frac{2E}{H^2}\frac{m}{e}$, so as to obtain the value of e/m.

Thomson's experiments made by the above method in 1899 led to a value of e/m for the negative ions emitted by an incandescent carbon filament which was not very different from that obtained from experiments on the cathode ray corpuscle, but in absolute value were too low. More recent measurements by Professor O. W. Richardson gave values $e/m=1{\cdot}45\times10^7$ and $1{\cdot}49\times10^7$, and more recent work still by Bestelmeyer, who used an improved method, has given the value $e/m = 1{\cdot}766 \times 10^7$ in E.M. units, and this is very close indeed to the best results for the cathode ray corpuscle, which, as we have seen, gives $e/m = 1{\cdot}77 \times 10^7$ in E.M. units. For full details of the latest and best work on this matter we may refer the reader to the book by Professor O. W. Richardson, *The Emission of Electricity from Hot Bodies* (Longmans, Green & Co.), in which the theoretical and physical side of the subject is most fully treated.

Summing up the results of twenty years' physical discovery on this subject, we may say that an exceedingly strong body of proof has been built up supporting the following statements :

1. The agency we call Negative or Resinous Electricity is atomic in structure, and the atom or smallest indivisible unit of it is called an electron ($=e$). The electron charge is equal to $4{\cdot}774 \times 10^{-10}$ of an electrostatic unit of quantity of electricity, or to $1{\cdot}591 \times 10^{-20}$ of an electromagnetic unit, or to $15{\cdot}91 \times 10^{-20}$ of a coulomb. It is the quantity of electricity conveyed by a hydrogen ion or atom of hydrogen in electrolysis, and is Nature's unit of electricity. A current of 1 ampere flowing for one second is equivalent to the passage of six million million million electrons across any section of the circuit.

2. This electron has a certain mass ($=m$) which is approximately 1/1,800 of that of a hydrogen atom, and is close to 9×10^{-28} of a gram.

The question has been much discussed whether the electron is anything else but a point-charge of electricity, and whether its mass is due to anything but the electrical properties of a moving charge of electricity.

7. If we consider a small sphere charged with electricity to be at rest, it exerts radial electric force which at a point at distance r from its centre is e/r^2, where e is the electric charge. When the sphere is at rest the lines of electric force are everywhere radial to the sphere. If the sphere is set in uniform motion with a velocity, v, then the moving charge is equivalent to an electric current, and it creates in surrounding space a magnetic force distributed in circles whose centres lie on the line of motion and planes are perpendicular to it. At a point at distance r, the radius vector making an angle θ with the line of motion, the

Article #27 shows detector measurements of how diodes having different values of Is and n perform as weak signal detectors when impedance matched at both input and out put.

#16 Published: 03/28/01; Revised: 02/10/2004

The center tap of the input transformer is not used in this circuit. The triode has grid leak bias. It is not possible to measure this bias with a DMM because of the large grid resistor, but the plate current is only about 280 μA. The diode and triode are referred to the negative end of the filament, but cathode bias is provided for the power pentode. The bias in operation is about -9.3 V, giving a plate current of about 5 mA and a screen current of about 1 mA. The output transformer can be any transformer on hand. I used the P-T31 that has been used in other places, which matches 8Ω to 5 kΩ. The load resistance should preferably be about 12 kΩ. However, it drove a good speaker at considerable volume with a rather small input. A three-tube battery radio could be made with this tube, an IF amplifier stage, and a pentagrid converter, a tube type which will be treated next.

magnetic force, H, due to the moving charge, has the value

$$H=\left(1-\frac{v^2}{c^2}\right)\frac{ev\sin\theta}{r^2\left(1-\frac{v^2}{c^2}\sin^2\theta\right)^{\frac{3}{2}}}$$

where $c=3\times10^{10}$ cms. per second, and e is the charge of the sphere. The proof of this formula is difficult, but has been given by Sir J. J. Thomson in his book *Recent Researches in Electricity and Magnetism*, p. 19, and also by Mr. Oliver Heaviside in his Electrical Papers.[1] It has been somewhat simplified by the author for his own University lectures.

If the velocity of the sphere is small compared with that of light ($=c$), then the above formula reduces to the formula of Ampère: $H=\frac{ev\sin\theta}{r^2}$ for the magnetic force of a current element, ev, at a point r, θ. If the sphere moves quickly, then the lines of electric force do not remain uniformly distributed round the sphere, but crowd up towards the equatorial plane, assuming that the direction of motion is that of the polar axis.

The sphere creates a magnetic field whilst it moves, and a magnetic field of strength, H, implies that there is energy equal to $H^2/8\pi$ per unit of volume in that field.

If we consider the velocity of the sphere is small, so that v^2/c^2 can be neglected in comparison with unity, then

$$\frac{H^2}{8\pi}=\frac{e^2v^2\sin^2\theta}{8\pi r^4}$$

To obtain the energy of the whole magnetic field, we have to integrate this expression throughout all space external to the sphere, which latter we shall suppose has a radius a. Calling this energy T, we have

$$T=\frac{e^2v^2}{8\pi}\int_a^\infty\int_0^\pi\frac{\sin^2\theta}{r^4}\,2\,\pi r^2\sin\theta\,dr\,d\theta$$

$$=\frac{e^2v^2}{4a}\int_0^\pi\sin^3\theta\,d\theta=\frac{e^2v^2}{3a}$$

[1] See J. J. Thomson, *Phil. Mag.*, 5th Series, vol. xi., p. 229, 1881; also Oliver Heaviside, *Phil. Mag.*, 5th Series, vol. xxvii., p. 324, 1889.

Accordingly, the whole kinetic energy of the sphere is

$$\tfrac{1}{2}\, mv^2 + \frac{e^2v^2}{3a} = \left(m + \frac{2}{3}\frac{e^2}{a}\right) v^2$$

The mass of the electrified moving sphere may therefore be regarded as increased by an amount $2e^2/3a$, due to its electrification. In the case of the electron the question which arises is, whether there *is* any other mass than that due to the magnetic field ?

Kaufmann measured, in 1901, the ratio of e/m for certain cathode ray corpuscles moving with high velocity and, later on, of others emitted by radium and has found that this ratio, e/m, is reduced in value as the velocity of the particle is increased ; and from this Sir J. J. Thomson and others conclude that the mass of the moving electron may perhaps be wholly due to the energy stored up in its magnetic field. If this is a fact, and if we assume a spherical form for the corpuscle, we can find its radius, a, for we have found the mass, m, of the corpuscle to be 9×10^{-28} gram, and its charge, e, to be $1{\cdot}59 \times 10^{-20}$ E.M. units. Therefore,

$$\frac{9}{10^{28}} = \frac{2}{3}\frac{e^2}{a} \text{ or } a = \frac{2}{27}\,\frac{(1{\cdot}59)^2}{10^{12}} = 1{\cdot}85 \times 10^{-13}$$

Hence the radius of an electron is of the order of one ten-billionth of a centimetre. The radius of an atom of matter is of the order of one hundred-millionth of a centimetre, and therefore the electron has a diameter of about one hundred-thousandth of that of a chemical atom.

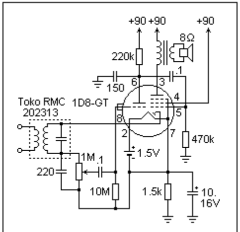
The dome of St. Paul's cathedral is about 110 feet in diameter, and that of St. Peter's at Rome about 170 feet.

The diameter of an ordinary small pin's head is about $\frac{1}{16}$th of an inch. If we imagine a great balloon having a diameter five times that of the dome of St. Paul's, or three times that of St. Peter's, then such a sphere would be as much larger than an ordinary pin's head as an atom of hydrogen is possibly larger than an electron.

These conclusions as to the volume of an electron are not, however, established with the same degree of certainty as is the case with its mass. Mr. A. H. Compton (see *Journal, Washington Academy of Science*, vol. viii., p. 1, Jan. 3rd, 1918 ; also *Science Abstracts*, vol. xxi.a, May, 1918, abs. 549) has given reasons for thinking that the electron cannot be a charged sphere of so small a diameter as 10^{-13}, but

connection. Diode bias is not suitable for high-mu triodes such as the 6AV6 or 6AT6, since they are very sensitive to the bias level. The 6R7 is a medium-mu triode (μ = 16). The 6SR7 is a single-ended equivalent, and will also work in this circuit. The signal generator should be adjusted to peak the output, at 455 kHz. I obtained an audio output of 13 V peak-to-peak with a 30% modulated AM signal of 0.2 V peak-to-peak, for a gain of about 289. The tuned circuit provides a large part of this gain.

The 6AQ6, 6AT6 and 6BF6 are all miniature dual-diode triodes with the same basing as the 6AV6, the 6BF6 being medium-mu and more appropriate for diode bias and transformer coupling. The 6SQ7, 6SR7 and 6ST7 are similar octal tubes, again all with the same basing. This was a very popular and useful tube type, with many options available.

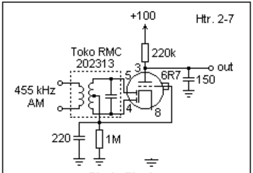


Detector - Audo Amplifier

The 1D8-GT diode-triode-pentode was designed to provide a complete audio system for a battery-powered radio. The circuit is shown at the right. The filament takes 0.1 A at 1.4 V, easily supplied by a D cell. The B+ supply is 90 V, for which batteries were available, consisting of 60 small cells. This circuit has a drain of less than 7 mA, which is quite acceptable, and hardly more than a transistor radio with the same audio output. The filament is hard to see when the tube is in operation. It can just be seen glowing orange in the diode portion of the tube. On one side is the diode with the triode on top; on the other is the pentode, all of which are clearly displayed. The tube cost $3.10, an excellent price considering all the experiments that can be done with it.

signal carrier frequency until the tuned circuit resonates; in my case, this was 500 kHz. For an input signal from the signal generator of 0.18V peak-to-peak (modulation amplitude 0.04V), I got 26V peak-to-peak at the plate of the 6AT6. The RF ripple was negligible, but there was some 60Hz pickup, not surprising with a high-gain breadboarded circuit out in the open. It was interesting to show the AM signal and the audio output simultaneously on the oscilloscope.

The circuit will function without the tuned circuit, as you can easily demonstrate. The signal generator output must then be increased, because the resonance gain is considerable. The circuit will also function with both diode plates connected to one side of the secondary, and the 1M potentiometer and filter capacitor to the other side. In this case, the ripple frequency will be halved, but the output voltage will be doubled. There is not a great advantage in using a full-wave detector. Look at the DC voltage across the potentiometer as the input amplitude is changed. This voltage, negative with respect to ground, can be used for AVC, automatic volume control, as is discussed elsewhere. With the full-wave detector, it varied from -0.5V for 10V p-p audio output to -1.0V for 30V audio output. In practice, the AVC voltage is further filtered to remove the audio.



Diode Biasing

The rectified signal voltage is of the correct polarity to provide grid bias for the amplifier tube in this circuit. Therefore, the grid of the triode can be connected directly to some point on the diode load resistor that provides the proper bias, in place of the volume control potentiometer and coupling capacitor shown above. This arrangement is called *diode bias*, illustrated by the circuit at the left. AVC is essential when diode bias is used, to keep the bias voltage in the proper range. The audio signal, of course, rides on the bias

may be a charged ring of a radius of about 2×10^{-10} cms. capable of rotating about any axis. If this is so, we may come back to some kind of Vortex-ring theory of electron structure as originally propounded by Lord Kelvin for the chemical atom.

8. Then, as regards positive electricity, there is evidence that this also is atomic in structure. The ratio e/m has been measured for positively charged corpuscles in a high vacuum tube, and it is found to be of the order of e/m for a hydrogen ion in electrolysis—viz., about 10^4. Hence positive electricity is associated with masses of the size of atomic masses.

The generally-held view at present is that an atom is a sort of solar system in miniature. The nucleus of the atom is a charge of positive electricity concentrated in a very small space, which may consist of one or more positive electrons.

The gravitative mass of the atom is chiefly due to this positive nucleus. Around this nucleus circulate a group of negative electrons like planets round the sun. If the number of negative electrons is sufficient to equilibrate the positive charge, then the atom is in a neutral electrical condition.

If the neutral atom is deprived of one or more negative electrons it is positively charged and constitutes a positive ion. If the neutral atom gains or takes up one or more negative electrons it becomes negatively charged and forms a negative ion. Chemical atoms have certain loosely-held or detachable electrons, which are called the valency electrons, and the view is very widely held that chemical attractions and combinations are due to electric forces acting between atoms, or groups of atoms, which have respectively gained or lost electrons.

In a solid metallic conductor, or conductor such as carbon, it is supposed that there is a continual exchange of negative electrons between neighbouring atoms. Electrons are, so to speak, jumping from atom to atom, and during their time of passage they constitute what are called the "free" electrons.

These motions take place in all directions, and the temperature of the body is determined by the kinetic energy of these free electrons. If an electromotive force acts on the conductor it applies a definite electric force to these free electrons, and over and above their indiscriminate motions a certain steady drift of electrons in one direction then takes place, which constitutes an electric current. These free electrons may be regarded as the molecules of a kind of gas existing in between the chemical atoms of the conductor. It has been, therefore, assumed that they obey the ordinary gas laws. The free electrons have a certain "mean free path" and a certain "mean square velocity," like gas molecules.

They do not at ordinary temperatures escape from the conductor because if any did, it would leave the conductor positively electrified, and this would tend to prevent the escape of more electrons.

But if the temperature of the conductor is raised the electrons may acquire such velocities that some are flung out beyond the attractive range of the positive ions left behind. This escape of the free electrons rises very rapidly with temperature, and constitutes what is now called the *thermionic current* from the incandescent wire. This current is measured by the quantity of electricity escaping per square centimetre per second from the surface of the incandescent wire or body.

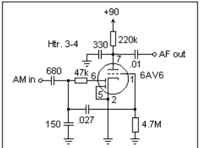
9. The study of the nature, variations and magnitude of this thermionic emission has been the subject of much investigation from a purely physical point of view.

As the chief purpose of the present volume is to direct attention to the technical applications of this phenomenon, we shall not occupy space with descriptions or discussions of the physical problems more than is necessary to explain the general principles involved. The experimental examination of the effect has been chiefly conducted by means of a simple apparatus, consisting of a straight metallic wire or carbon filament which is attached to platinum electrodes and sealed into a glass cylindrical bulb in an axial position.

Surrounding the filament is a tubular electrode made of metal, generally platinum, and this cylinder has a metallic connection made to it by a platinum wire welded to the cylinder and sealed through the glass (see Fig. 22).

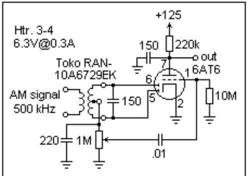
The glass vessel can be exhausted to various pressures through a side tube or filled with various gases. If the surrounding metal cylinder is not employed, and if the wire

and maximum plate dissipation of 0.5 W. The maximum cathode current is not specified, but should not exceed a few milliamperes. The tube has an unusually high plate resistance, and the amplification factor is over 100. It is a good triode for a voltage amplifier. My example gave g_m = 1.3 mS, r_p = 67k, μ = 90 at about 500 μA plate current, and V_g = -1.0 V. The transconductance varies strongly with plate current, reaching 2.2 mS at 1 mA, where μ = 116.



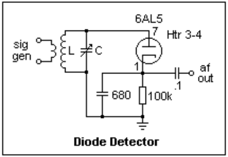
Diode Detector and AF Amplifier

A detector-amplifier circuit is shown at the left. This circuit is fed by a signal generator at AM in, and the audio output is taken from AF out. The amplifier uses grid-leak bias, which effectively clamps the peak of the audio wave at 0 V. The stronger the input signal, the more negative the grid bias, which makes the most of what is there. With an AM input of peak value 0.95 V and modulation amplitude 0.37 V, the peak to peak output was 3 V, for a gain of -8, which is quite good. I used a radio frequency of 2 MHz, and modulation of 1 kHz. At lower radio frequencies, the filtering of the output becomes progressively worse; this could be optimized if desired. This detector gives good fidelity with high sensitivity.



Full-Wave Diode Detector and Amplifier

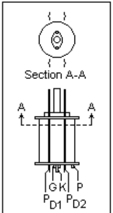
A full-wave diode detector is shown at the right, using transformer input. The 6AT6 is similar to the 6AV6, but its mu is 70 instead of 100. The transformer is a Toko RAN-10A6729EK, available from Digi-Key. It is specified as 0.63 mH, and for 200 kHz. Adjust the bias detector, however, the FET is suitable, and a BJT biased near cutoff makes an excellent detector, as we saw in the page on Amplitude Modulation.



Diode Detector

A diode detector, using a standalone diode, is shown at the left. The output is the same amplitude as the modulation on the carrier that is input, very closely, so the detector could not do any better. Often, the diode was included in the first AF amplifier tube, sharing the same cathode, and dual diodes were also available for full-wave detection, which doubles the output. If you have a tuned circuit at this point, it would be easy to test a diode detector, and high voltages are not required, just the heater power. A solid-state diode would work the same way, but the 0.7 V drop would make it less sensitive, and it would not even respond to weaker signals. Using a Ge diode (1N34A) would help, but not eliminate, the problem. The thermionic diode is ideal in this application.

The typical superheterodyne receiver used a diode detector, followed by an audio voltage amplifier. These functions were usually combined in a single envelope, the diodes and the amplifying triode or pentode sharing the same cathode. A very good tube of this type was the 6AV6, whose structure is shown at the right. The diode plates are at the top of the envelope, with the cathode easily seen between them. The IF output was usually from an air-core, slug-tuned transformer, making it easy to use full-wave rectification. Only one of the diodes could be used for half-wave rectification, which was usually quite adequate. The triode is a high-mu triode with a maximum plate voltage of 300 V,



6AV6 Structure

or filament is heated by an electric current passed through it, then the ions or electrons given off by the wire would accumulate to a certain extent in the space, vacuous or gas-filled, round the wire and create a *space electric charge* which would soon prevent any further emission. This explanation of the limitation to the increase of the thermionic emission was first given by Mr. C. D. Child in 1911 (see *Physical Review*, vol. xxxii., p. 498, 1911).

By employing the metal cylinder we can make a definite difference of potential between the heated wire and the cold cylinder, and, therefore, an electric force so directed as to urge the ions from the wire to the embracing cylinder. The arrangement has also the convenience that we can determine the temperature of the incandescent wire by measuring its resistence or ratio of volt-drop down the

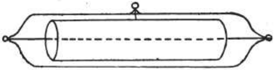


FIG. 22.—Exhausted tube having in it a metal cylinder and concentric incandescent tungsten wire to show the thermionic emission from the wire.

filament to current through it, or else by making the filament one arm of a Wheatstone's Bridge arrangement.

If we have previously determined the resistence of the filament at several standard temperatures we can by interpolation or extrapolution determine its temperature corresponding to other resistances.

Such an apparatus is a convenient modification of the lamps used by the author or by Sir William Preece in examining the Edison effect.

As soon as experiments began to be made with the above apparatus it was found that the observed effects were complicated and depended upon a great many factors, such as (1) the material of the wire or filament heated, (2) its temperature, (3) the gases or impurities occluded in it, (4) the nature of the gas surrounding it, (5) the pressure of this gas, and (6) the previous treatment of this wire as regards heating and exhaustion.

Broadly speaking, we may say that when the pressure of the gas in the bulb is not extremely small—that is, when the vacuum is not extremely high—the effects will be complicated by the ionisation of this gas by the electrons emitted by the wire or filament, and this will give rise to positive and negative ions in the surrounding gas.

It soon became clear that to simplify the phenomena the removal of all gas round the heated wire and all gas films from the interior surfaces in the vessel and occluded gases from the materials was essential. This can only be done by prolonged heating of the whole apparatus and most careful exhaustion.

For this purpose very perfect mechanical vacuum pumps, such as the Gaede pump, must be employed and the exhaustion completed by the use of chemical means or by Sir James Dewar's method of absorption of residual gases by charcoal, particularly cocoanut charcoal fragments, cooled in liquid air (see chap. ii., sect. 9).

It is also necessary to heat the experimental vessel in an electric furnace, or by other means, during the exhaustion, and to prevent the collapse of the glass tube this may have to be done in a vacuum electric resistance furnace. The greatest difficulty is to eliminate occluded air or gas from the metal collecting cylinder.

As these precautions are equally necessary in the construction of thermionic detectors used in radiotelegraphy a few more details may be given. It is an extremely difficult matter to heat a metal collecting plate which is sealed up inside an exhausted glass vessel sufficiently to expel occluded gas by mere external heating. It is easier to do it if the collecting plate is formed of a wire coiled into a close spiral with turns nearly in contact, because then both ends of this wire can be welded to platinum wires which are sealed through the glass, and we have then access to the terminals of the spiral wire and can heat it intensely by an electric current passed through it.

We can then aid the exhaustion by the method of Sir James Dewar, connecting the glass vessel to a glass bulb filled with crushed fragments of cocoanut charcoal (see chap. ii., sect. 9). This bulb has to be hermetically sealed to the thermionic vessel. When the vacuum has been made as high as possible by the pump the charcoal bulb can be immersed in liquid air and will absorb the residual gas. By

(from 1M to 3M) or grid capacitor (100 pF to 220 pF). The grid bias with no signal was about -0.5 V with a 1M grid resistor.

The circuit works by using the small grid current when the grid is slightly negative. This grid current increases rapidly and very nonlinearly, so square-law detection is possible. The grid resistor establishes a quiescent point around which the signal oscillates. The rf part is bypassed through the grid capacitor, while the af part remains and causes a voltage drop across the grid resistor, which is then amplified in the usual way. With a 100k plate resistor, the output af voltage could approach 1 V peak-to-peak. Another stage of audio amplification would give a quite satisfactory result, but I was hoping for one tube. (The 12AX7 has two triodes in the same envelope--if such a tube were used, the receiver would be, strictly speaking, single tube.) With most other kinds of detectors, such a hope would be quite vain, it must be admitted.

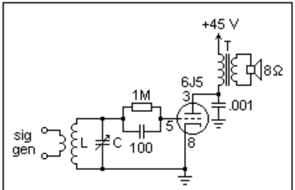
If the input signal amplitude is increased, the grid bias starts to decrease because the grid becomes positive on the peaks, and the detection becomes a little more linear. If the grid is biased to cutoff with a C supply, then there is clear linear detection, since the signal is effectively rectified. Such a circuit is called a grid-bias detector, and the signal amplitude must be restricted so that the grid does not go positive, when distortion would result.

You may notice in the tube manuals that a "maximum grid resistance" is given for a tube; for the 6J5, it is 1M. The reason for this is positive ion current, which may drive the grid more positive in a resistance-coupled amplifier, disturbing the bias. This is not a maximum in the same sense as the maximum plate dissipation or maximum cathode current are, since damage to the tube is not in question. There is no trouble in the grid leak detector, and values of several megohms are permissible.

There is no analogy to the grid-leak detector with FET's, which otherwise behave pretty much like vacuum tubes, because the leakage current is far too small for the desired behavior. As a gateactual circuits that used a 1V6, but the amplifier shown at the left may be studied. It gave a gain of -14 with a plate current of 357 μA, so the effective transconductance was 298 μS. I substituted a 100k plate resistor, but the gain only increased marginally, to about -17. By experimenting, you may be able to get more gain from the tube. At low plate currents, the amplifier oscillated in an odd manner, and there were other peculiarities seen while fiddling around, but I did not take the time to track them down.

The Grid-Leak and Diode Detectors

Detectors are discussed in Amplitude Modulation, where the two types of square-law and linear are explained, and the grid-leak detector is mentioned. A circuit using a 6J5 triode is shown at the right. The audio output transformer T can be replaced with a 10k or 100k resistor, and the output observed with an oscilloscope. I could find only a 1k to 8Ω transformer, really designed for use with transistors. The circuit works, but I was not impressed by its output. Asking for loudspeaker output from a detector is being very optimistic, but I had some hopes. Perhaps a more suitable transformer would give better results.



Grid-Leak Detector

The tuned circuit can be one from a crystal set, with a loopstick and variable capacitor. The signal generator is coupled by about 9 turns slipped over the loopstick, providing an AM signal about 30% modulated with 1 kHz, in the broadcast band. The output was roughly constant, no matter what the plate voltage (45 to 105 V), input amplitude, value of grid resistor

long-continued heating and pumping it is possible to reach a state in which the pressure of the residual air does not exceed 10^{-6}, or even 10^{-8}, of a millimetre of mercury. As the diffusion of the rarefied air along connecting tubes is slow the exhaustion and simultaneous heating of the bulb to about 60° C. may have to be continued for several days. At the same time an electric current must be passed through the wire or filament of carbon to heat it and to expel from it all absorbed gases or volatile material.

Tungsten forms a very suitable material for the incandescent wire. This metal has a very high melting point (3270° C.), vastly higher than that of platinum (1755° C.) and higher than the temperature at which carbon begins to volatilise rapidly. Tungsten is very non-volatile and can be heated for long periods to a very high temperature without change. It is possible therefore to obtain from it very large thermionic emission, as much as a coulomb or more per second per square centimetre of surface. A thermionic current of the above strength implies the emission of 6×10^{18} electrons per square cm. per second. We shall presently discuss the origin of these electrons.

If in such an apparatus as above described we pass a current through the wire and heat it to a known absolute temperature T, and if we apply a battery of known voltage to send a negative current from the hot filament to the cold cylinder and measure the thermionic current we can plot out in the form of a curve the relation between thermionic current and potential difference (P.D.) between the filament and cylinder. If the vacuum is very high so that secondary ionisation effects are avoided we find that the curve so delineated resembles in form the magnetisation curve of iron. The thermionic current increases at first slowly, then more quickly, but finally attains a nearly constant value, which is not exceeded provided no secondary ionisation takes place (see Fig. 23).

When this point is reached the current is said to be *saturated*, and it has been found that this saturation current has a definite relation to the absolute temperature T of the hot body.

Proceeding on certain physical hypotheses, Professor O. W. Richardson[1] has deduced the following formula for

[1] See *Phil. Trans. Roy. Soc. Lond.*, vol. cci., p. 516, 1903.

the saturation current I per square cm. in terms of T and certain constants C and b: $I=C\sqrt{T}\,\epsilon^{-b/T}$, where ϵ is the base of the Napierian logarithms. We can also reckon I in its equivalent in number of electrons per second per square centimetre N, and write $N=A\sqrt{T}\,\epsilon^{-b/T}$.

By multiplying N by the electronic charge $e=4\cdot8\times10^{-10}$ and then dividing by 3×10^{-6} we reduce to milliamperes per square centimetre of surface ($=i$).

The value of the constants A and b have been determined for various materials.

For a *platinum* wire Richardson found $A=7\cdot5\times10^{25}$, $b=4\cdot93\times10^{4}$; for a *carbon* filament he found $A=10^{34}$, $b=7\cdot8\times10^{4}$; whilst for a *tungsten* wire Langmuir has

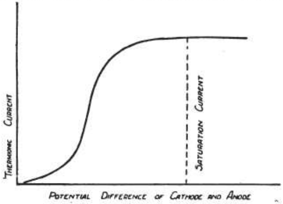


FIG. 23.—Characteristic or Volt-ampere Curve of a highly rarefied gas or nearly perfect vacuous space.

found $A=1\cdot55\times10^{26}$, $b=5\cdot25\times10^{4}$; and for *tantalum* $A=7\cdot45\times10^{25}$, $b=5\times10^{4}$.

The constant b seems in all cases to be of the order of 50,000, but A is very variable.

Either of the above formulæ for I or N gives results in very fair agreement with observation.

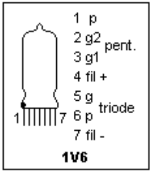
It will be seen that the electronic emission from the heated wire rises up very rapidly with increase of temperature, and hence the advantage in technical applications of employing a material like tungsten which can be heated without alteration to a high temperature.

Sir J. J. Thomson has shown (see *Conduction of Electricity Through Gases*, p. 166) that from the known values of the

transconductance varies considerably with plate current, which gives rise to distortion for large signal amplitudes.

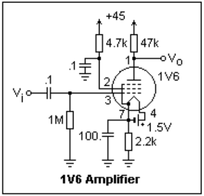
These tubes make vacuum-tube experiments very easy without requiring high-voltage supplies, only what is found in a normal transistor lab.

Sub-Miniature Tubes



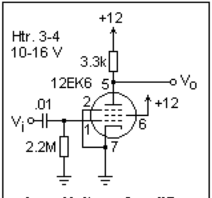
The smallest regular electron tubes were the *subminiature* tubes, designed for battery-powered portable apparatus, from hearing aids to radiosonde transmitters. Typically, the lead wires were brought out through the press seal without a base, but there was also a subminiature base used for a few tubes. As an example, you can work with the 1V6, a pentode-triode with a filament taking 40 mA at 1.25V (the filament supply can be a D cell). The tube is 40mm x 10mm x 7mm, approximately. The maximum plate voltage is 45V, and typical plate currents are less than 1 mA.

A sketch of the 1V6 and its connections is shown at the right. On the press seal, there is a red dot that identifies what I have called pin 1. The filament is located at the center of the tube, with the pentode on one side and the triode on the other. The triode shows a μ of about 10, r_p = 18.6 kΩ, and g_m = 440 μS. The pentode has g_m as high as 694 μS above 500 μA plate current, but it drops considerably at lower plate currents. The two devices can be tested as usual, taking care not to exceed 45V or 1 mA. Note that the pentode and the triode share the same filamentary cathode.



Unfortunately, I do not have any

charge grid tetrodes, behaving like triodes. The other tubes are of conventional construction, in general having low plate currents, less than 1 mA in many cases. These include twin-diode triodes (12AE6, 12FK6, 12AJ6), sharp cutoff pentodes (12AF6, 12BL6, 12CX6, 12EK6), remote cutoff pentodes (12CN5, 12DZ6), twin-diode remote cutoff pentode (12F8), pentagrid converter (12AD6), pentagrid (variable gain) amplifier 12EG6, and a twin-diode power screen-grid tetrode, 12J8. The last tube can deliver 20 mW output power, half of what the 12DL8 can do.



Low-Voltage Amplifier

The 12EK6 (also known as 12DZ6 and 12EA6) is a screen-grid pentode for low-voltage use. A voltage amplifier using this tube is shown at the left. This tube was generally used as an IF or RF amplifier, so the load would have been a resonant circuit, not a resistor, giving much higher gain. However, the resistive load is easy to experiment with. There is no voltage to waste for cathode bias, so grid-leak bias is used. When a signal is applied, the bias will adjust itself so that the top of the input waveform is clamped to 0 V. Vary the input amplitude to verify this. This circuit works with an input of up to about 2 V peak-to-peak, perhaps best for an input of around 1.0 V p-p. The output voltage is then about 5.8 V p-p, the plate potential is 6.0 V, plate current 1.8 mA, and gain about -5.5, corresponding to a transconductance of 1.8 mS, about right from measurements of the characteristics and the position of the operating point in this case. The transfer characteristic is rather curved, leading to considerable distortion for larger amplitudes. Nevertheless, it is remarkable that the circuit works so well at such a low voltage.

As a triode (plate, suppressor and screen connected together), the 12EK6 has μ = 8.5, g_m = 6.3 mS and r_p = 1.35 kΩ. The

constants A and b in the Richardson formula we can determine the number of free corpuscles or electrons (N) per unit volume of the metal or material used for the heated filament, and also the work (w) required to drag or force an electron out of the metal. Thus from experiments on a platinum wire by Richardson which gave $A=1{\cdot}5\times10^{26}$, $b=4{\cdot}93\times10^{4}$, Thomson deduces $N=1{\cdot}3\times10^{21}$ and $w=8\times10^{-12}$ erg.

Broadly speaking, it appears that the number of free electrons in a conductor in any volume is of the order of the number of atoms in the same space.

10. A matter which has been very much discussed is the origin of these negative ions or electrons emitted by a highly-heated metallic wire or carbon filament.

It was found by H. A. Wilson that the thermionic emission from an incandescent platinum wire was greatly increased by admitting hydrogen gas into the vessel, and similar effects have been noticed for heated palladium and sodium. Langmuir, however, found a great reduction in the emission from tungsten when hydrogen was present in the vessel, which he ascribed to secondary chemical actions. Some observers have attributed the thermionic emission from carbon to the action of gases occluded in the material, and stated that when the carbon is freed from these gases the thermionic emission is greatly reduced.[1] O. W. Richardson has, however, criticised these conclusions and shown that the reduction of electronic current in the case of the experiments of Pring and Parker can be accounted for by the deflection of the electrons due to the magnetic field of the current itself, causing incandescence in the carbon conductor (see Richardson, *The Emission of Electricity from Hot Bodies*, pp. 65 and 130). Richardson concludes from very careful experiments that there is no certain proof that the thermionic emission from metals or carbon is the direct result of chemical action, but that it is a thermal phenomenon when carried out with pure materials in a high vacuum. Nevertheless, the emission is enormously affected by the presence in or around the incandescent wire of other substances.

Thus, A. Wehnelt in 1903 and 1904 investigated the

[1] See J. N. Pring, "The Origin of Thermal Ionisation from Carbon," *Proc. Roy. Soc. Lond.*, vol. lxxxixA, p. 344, 1913; see also Pring and Parker, *Phil. Mag.*, vol. xxiii., p. 199, 1912.

thermionic emission from platinum wires coated with oxides of calcium, barium or strontium, and found that in vacuo such oxide-coated wires emit far more corpuscles or electrons per sq. cm. per second than a pure platinum wire at the same temperature (see *Phil. Mag.*, vol. x., p. 80, 1905). He found that otherwise the thermionic saturation current from these oxide-covered wires was related to the absolute temperature in accordance with Richardson's exponential formula already given. There is a very copious emission of negative ions from the glower of a Nernst lamp, which glower consists of oxides of rare earths. This has been investigated by G. Owen.[1]

It is easy to show this effect with a Nernst glower heated by a direct current. If a Nerst glower is supported with the bare glower in a horizontal position placed within a few millimetres of the bottom of a metallic insulated vessel kept cold by being full of water, and if one terminal of a galvanometer is connected to the positive terminal of the glower and the other to the cold vessel, a considerable thermionic current will be found passing through the air even at ordinary pressures.

It has been stated that Langmuir found heating a filament containing thorium in the neighbourhood of a tungsten wire increases the thermionic emission of the latter a million-fold (see *Nature*, vol. xcviii,, p. 146, Oct. 26th, 1916).

Apart from the effect of such admixtures or surface coatings on the thermionic current from a wire, we have to note the effect of the surrounding rarefied gas upon it when the difference of potential between the incandescent filament and the collecting plate is made sufficiently great. In that case the ions or electrons projected from the filament ionise the gas molecules, and the negative ions so produced are carried by the electric force up to the collecting plate and will then increase the apparent thermionic current. This is generally represented by that stage in the curve connecting P.D. between hot wire and plate and the thermionic current at which the curve begins to rise very quickly. The curve in Fig. 24 shows the results of some experiments by McClelland in 1902 on the emission of positive electricity from a wire which exhibits a third

[1] See G. Owen, *Phil. Mag.*, vol. viii., p. 230, 1904, "On the Discharge of Electricity from a Nernst Filament."

The screen grid potential is above the plate's in this circuit. Pentodes offer the capacity for controlling the plate current through the screen voltage, so that the plate voltage can be what is required. For higher voltages, the screen grid is normally at the same or lower potential as the plate, on the average. The grid voltage cannot be measured accurately with a DMM or scope, since the bias conditions will be disturbed. However, you will find that the amplifier works very well. Measure the gain the usual way, with a function generator and oscilloscope.

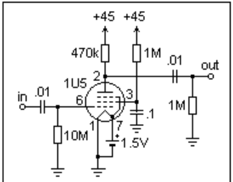
Radios for motor cars had 6 V DC available, which was right for 6.3 V heaters, but could not be used for the B supply--even now, 6 V is inconveniently low for transistors. The usual solution was a *vibrator* supply. Contacts on the magnetically-driven vibrator armature converted 6 V DC to alternating current, which was stepped up by a transformer and then rectified to DC again (sometimes by contacts on the vibrator) for the B supply. Vibrators were electrically very noisy, and had short lives, but were widely used until solid-state equivalents became available. They came in cylindrical metal cans, and looked like electrolytic capacitors. The 0Z4, mentioned elsewhere, was a rectifer specifically for vibrator supplies. Another possibility was the *dynamotor*, a motor-generator with a single rotating armature and brushes, which could supply more power than a vibrator and was more reliable. However, they were too expensive for general commercial use, though widely used in the military.

When 12 V became the automotive standard, vibrator supplies or their solid-state equivalents, could still be used. Tubes with 12.6 V heaters were already common. Many had the heater center-tapped, so they could be used equally well on 6.3 V. However, 12 V is high enough to be used directly as the plate supply if the tubes are specially designed. A range of tubes was produced that could be used on 12 V only, without any high voltage at all. We have already discussed the 12DL8 and 12K5 space-charge-grid tetrodes, and how the space-charge grid allows larger plate currents for small plate voltages. There were approximately 15 tube types designed for 12V use, of which only three, the 12DL8, 12DS7 and 12K5 are space-

110V, but this can be exceeded a little in testing. I measured the characteristics for plate voltages of 125V and less, at grid voltages of 0.0, -0.5 and -1.0V (relative to the negative end of the filament). The plate current was always less than 1 mA. My results were μ = 62, g_m = 340 μS, and r_p = 182kΩ. These values are close to the published values. The characteristics are noticeably curved in this region, so the parameters will vary with plate current. The apparently low value of transconductance is quite reasonable for the small plate currents at which the tube is used.

The amplifier shown gave a voltage gain of G - -40, with an input of 0.4V peak-to-peak. The plate current was about 100 μA, which made the plate voltage 77V and the grid bias -0.26V. The bandwidth of the amplifier was quite good, roughly from 10Hz to 50kHz. It should be noted that the total power drain of this circuit is no more than 83 mW, of which most is the filament power. This is very economical for a normal-sized tube. The tube remains quite cool in service, incidentally.

A pentode voltage amplifier with a gain of about -33 is shown at the right, using a 1U5, a sharp-cutoff pentode which comes in a 7-pin miniature package. Note the polarity of the filament supply, which is important, since it supplies a little grid bias as well. Since the voltages and currents are low, you can use the same 1/4W resistors used with transistors. The capacitors must have an appropriate voltage rating, of course. The 10M resistor is a "grid leak" that will prevent the grid from going positive. It charges on the positive excursions of the grid to provide whatever bias is necessary. The plate current was 61 μA, and the screen grid current was 20 μA.



Pentode Voltage Amplifier

stage in the characteristic curve when the thermionic current begins to increase again after one saturation stage has been reached.[1] This appears so be due to the production of fresh ions from the surrounding gas. The result of exhaustive experiments has, however, shown that in the highest possible vacua, when using carefully prepared and long-heated tungsten wires as heated filaments, the thermionic emission is entirely due to electrons coming from the metal, and at a sufficiently high temperature may reach even 3 or 4 amperes per square centimetre of surface of the incandescent wire.

A question, then, which has peculiar interest, is the source of these emitted electrons. O. W. Richardson has conducted and described special experiments, made with the object of obtaining an answer.[2] A very carefully

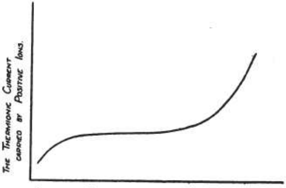


FIG. 24.—Characteristic curve for vacuous space not very highly exhausted. The final rise in the curve is due to gas ionisation by the applied voltage.

prepared tungsten filament was used, heated in a high vacuum, in which the pressure was less than 10^{-7} of a millimetre of mercury. The filament gave out an electronic current of 0·5 ampere for 30 minutes or 1,800 seconds, equivalent to 900 coulombs. This implies the total emission

[1] See J. J. Thomson, *Conduction of Electricity through Gases*, 1st Edition, p. 186.

[2] See O. W. Richardson "On the Emission of Electrons from Tungsten at High Temperatures," *Phil. Mag.*, vol. xxvi., p. 345, 1913 also his book, *The Emission of Electricity from Hot Bodies*, p. 133.

of 54×10^{20} electrons or 3×10^{18} electrons per second. Richardson carefully discusses in this paper, in the light of numerical values, the possibility of these electrons having come from the atoms of the tungsten evaporated, or from the ionisation of the residual gas, and shows that both these suppositions are inadmissible. In one experiment 984,000 electrons were emitted per atom of tungsten evaporated. He came to the conclusion that these electrons could only have come into the tungsten from other portions of the electric circuit, of which it formed part; in other words, that the electrons emitted are the "free" or conductivity electrons of the metal.

11. The subject of the emission of positive ions from incandescent wires has no such great practical interest at present as that of the emission of negative corpuscles or electrons, but reference must briefly be made to it.

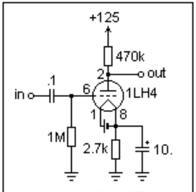
We have seen that when a platinum wire is heated to a red heat in vacuo it gives off, at first, positive electricity, and this is quite distinct from any subsequent production of positive ions in the surrounding gas. This positive emission is, however, a short-lived effect. It does not remain constant, but rapidly decays away with time. A wire which has lost the power of positive emission will regain this power if heated in air or in a Bunsen flame. It is clear from measurements made of the ratio, e/m, for these positive ions that they are masses of atomic magnitude and appear to owe their origin to gases occluded in the heated wire or resulting from interaction between the atoms of the heated wire and the surrounding gas. The reader desiring to make a further study of this portion of the subject will find a valuable collection of experimental results in Professor O. W. Richardson's book, and in latest editions of Sir J. J. Thomson's book on *Conduction of Electricity through Gases*, and in his smaller book, *The Corpuscular Theory of Matter* (Constable & Co.).

A very readable account of the electron theory of electricity is given in Mr. G. W. de Tunzelmann's book, *A Treatise on Electrical Theory* (C. Griffin & Co.). In Thomson's book on *The Corpuscular Theory of Matter* will be found a particularly full discussion of the electron theory of electric and thermal conduction.

Battery Tubes

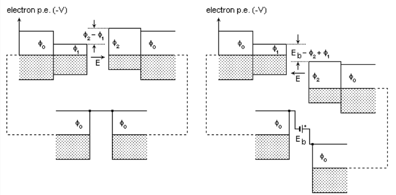
In the early days, nearly all radios (and other electronic apparatus) were powered by batteries, usually primary cells. With the rise of central power distribution, apparatus could be powered (and storage batteries charged) from the AC line, which was a practically unlimited, cheap source so far as radios were concerned. Transformers made high-voltage power supplies easy to build. Low-voltage filaments were largely replaced by 6.3V heaters and unipotential cathodes since power was now cheap. However, there still remained a demand for portable radios beyond the reach of power lines, and these were necessarily powered from batteries. The emphasis here had to be on small power drain, since battery power is expensive. Typical batteries were 1.5V and 3.0 V for filaments ("A" batteries), and 45V or 90V for plate supplies ("B" batteries), both the usual Leclanche "dry" cells. Filaments were generally used, because of their much greater efficiency in mA per watt. Typical battery tubes had filaments taking only 50 mA at 1.4V, only 70 mW. Plate currents were not high, since a few mA would be quite sufficient. For experiments with battery tubes, a D cell in a holder is an adequate filament supply, good for about 100 hours of service. Even an AA cell will do for experiments.

The 1LH4 is a loktal battery triode, which is shown in a voltage amplifier at the left. A similar octal tube is the 1H5-GT, and either will do in this experiment (but the basing is different!). A diode plate is included, connected to pin 4, and using the negative side of the filament as its cathode. The diode is not used in this circuit. The maximum plate voltage is



Voltage Amplifier

DMM, it would show 0 V and, of course, no current would flow. However, the Fermi levels of all three metals must line up for equilibrium, making a level surface on which the electrons will not tend to roll one way or the other. It is clear that in this state of equilibrium, the surfaces of metals 1 and 2 will not be at the same electrostatic potential. An oxide-coated cathode has a work function of about 1.0 V, while a nickel plate or grid has a work function of about 5.0 V. When the Fermi levels align, the cathode is 4.0 V positive with respect to the other electrode.



Effects of Contact Potential

At the right, we have connected a source of emf E_b into conductor 0. A source of emf maintains a difference in the Fermi levels equal to its voltage. With the polarity shown, the cathode 1 has now become negative with respect to the anode 2, by an amount equal to the applied voltage less the difference in work functions. If the device is a thermionic diode, current can now flow from cathode to anode. The actual plate voltage is about 4 V less than the meter says, because of the contact potential. In practice, things are a bit more complicated, because of space-charge effects. When you measure the V-I characteristic of a diode, there appears to be a small positive plate voltage when the measured voltage is zero, and a little current flows. The reason is that the electrons are emitted with some kinetic energy, and a negative space charge is created around the cathode. The actual emission to the anode comes from the minimum of this potential well, which is several volts negative, and so the plate may be slightly more positive than this minimum, in spite of contact potentials.

INSIDE THE VACUUM TUBE

BY

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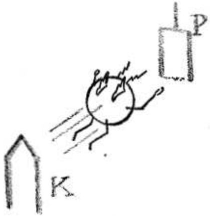
Baxter Rowe

1945

JOHN F. RIDER PUBLISHER, INC.
404 Fourth Ave. New York 16, N. Y.



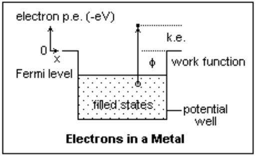
Chapter 6

THE DIODE

THE MATERIAL GIVEN thus far in this book has prepared us for what shall follow in this and subsequent chapters. We have, up to now, given certain facts relating to the operation of the vacuum tube: the manner in which and the reasons why, the electrons, so essential to the vacuum tube, are liberated; the basic reasons for the movement of electrons between charged surfaces, that is, the underlying basis for plate current within the vacuum tube. True, we have not as yet, mentioned *types* of vacuum tubes, but the specific type has very little to do with the principles which govern the motion of the electrons.

We are now ready to investigate what happens in the different types of vacuum tubes and to investigate the variation in the magnitude of the inter-electrode electron stream as the result of changes in the strength of the electrostatic fields which exist in the vacuum tube. In practical language, these electrostatic fields are referred to in terms of voltage,—*operating voltages* and *control voltages*,—and the changes in the magnitude of the electron stream within the vacuum tube are referred to as *changes in plate current*. Almost all of the essential conditions normally associated with the operation of the tube are

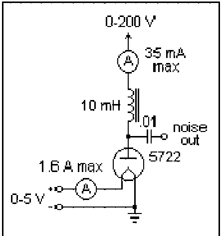
free electrons, but differ by up to a few volts from the true potential differences.



To understand this, let's review electrons in metals. One or more of the outer electrons of each metal atom is free to wander in the field of the ion cores, effectively binding the metal together. The positive ions create a potential well, as shown in the figure, and the electrons occupy the states of lowest energy. Note that electron energy increases upwards; since electrons are negatively charged, this means that voltage gets more negative upwards. There are not many more states than electrons, so they fill up the states up to some energy called the Fermi energy at 0 K. At ordinary temperatures, there is little difference, since the thermal energy is small compared to the kinetic energy of the electrons near the Fermi level.

If an electron is given enough energy, by thermal agitation or absorption of light, it may be separated completely from the metal and wander freely. The amount of energy necessary to just get outside is called the *work function*. Anything more goes into kinetic energy of the electron. The free electron can now be accelerated or decelerated by electric fields outside the metal in space. Work functions measured by thermionic, photoelectric and contact potential measurements agree roughly, but they depend sensitively on the surface preparation.

What happens in a vacuum tube is illustrated in the figure below. Suppose metal 1 is the cathode and metal 2 is the anode or grid, and the connections are made by a third metal 0 (there could be several such metals, but they all will act like metal 0). At the left, metals 1 and 2 are connected by a wire of metal 0. If metal 0 includes a should be rated at 2 A or more. Increase the filament voltage gradually, looking for the glow. There will be no plate current until the filament current reaches about 1.3 A, but it increases very rapidly beyond this point. The filament glows brilliantly, like an incandescent lamp, since its operating temperature is about 2400K, not the 900K of an oxide-coated filament. The filament current should not be allowed to exceed 1.6 A. If the power supply has current limiting, it can be useful here. By setting the plate voltage at near 200 V, you can see the saturation current as a function of filament current.



Testing the 5722

For two or more reasonable values of the saturation current, say 5 mA, 12 mA and 20 mA, record the current as a function of plate voltage and plot your results. For I_f = 1.5 A, the plate current saturated for about 50 V on the plate, approaching a value of about 12 mA. It is easy to find out what plate voltage to use to ensure saturation when making shot noise in this way. It is very difficult to make noise measurements in the usual breadboarding environment. I thought it just possible to have seen some on my 100 MHz scope with a plate current of 20 mA, without amplification. See the page on Noise for more discussion of noise measurements.

Contact Potential Effects

This is a good place to mention contact potentials, since you will probably run into their effects when experimenting with low-voltage tubes. Because of contact potentials, the voltages you measure with a DMM are not the actual voltages between electrodes, as seen by the

considered in connection with the plate current. That which we call the operating characteristics, the behaviour of the tube, is usually interpreted in terms of the plate current.

This fact will become indelibly impressed upon you as you progress through this section. You will see how even the selection of the electrical components associated with the vacuum tube, but located outside it, are chosen because of the facts which are learned from a study of the behaviour of the plate current within the vacuum tube when the tube is operated in a certain manner. In fact, observation of the plate current by means of special electrical devices, gives an excellent insight into the actual performance of the vacuum tube.

The Diode

Of the many types of tubes which are in use, the simplest is the *diode*. This is a two-element tube, invented before 1900 by J. A. Fleming, and which consists of an *emitter of electrons* and a *collector of electrons*. The term diode, by the way, refers to *the number of elements* within the tube envelope rather than to the specific application of the tube. Many different names are applied to the diode which indicate the specific function of the tube in any particular electrical circuit. For example, the diode may be used in one circuit to perform the function of developing an automatic-volume-control voltage; hence it would be called the *avc tube* without necessarily stating that it is a diode. That it is a diode would become evident upon an examination of the wiring diagram of the system which would show the symbol for such a tube. There are many more such occasions wherein the diode is known as a *rectifier, demodulator, detector*, etc. So, when discussing the basic diode, we have no particular application in mind. These we will consider later.

The two elements which comprise the diode have more than one name. The electron collector is known as the *plate* or the *anode*, while the electron emitter, if of the indirectly heated type, is called the *cathode;* while if of the directly heated type, is generally spoken of as the *filament*. However, the electron emitter is called the *cathode* without any special consideration being given to whether the emitter is indirectly or directly heated. Today this usage seems quite natural in that by far the greater number of tubes in use are of the indirectly heated type. In fact, it is our intention, as we have already mentioned, to consider the electron emitter in the vacuum tube to be of the indirectly heated type, and we shall therefore, unless statement is made to the contrary, always have that in mind.

Cathode and Filament Structure

The types of cathode, heater, and filament structures that are used in the diodes we shall discuss are quite generally employed in most of the "small" tubes, so that it might be well to describe these constructional features in this chapter and thereby avoid duplication later. However, before discussing them, it might be well to mention that some special types of diodes do use cathode systems somewhat different in physical design from those to be illustrated.

Directly and Indirectly Heated Tubes

In the directly heated tubes, the filaments are of the general construction shown in Fig. 6-1. The filaments themselves are built in the

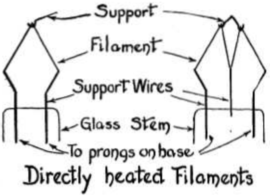


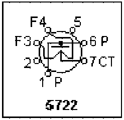
FIG. 6-1. Directly heated filaments are of two main types. That one shown at the left is an inverted V and the one at the right is an inverted W. The supports at the tops of the filament wires are erected from the tube base.

form of an inverted V or W, being mounted and held in place by suitable metal supports which rest in the glass stem of the tube. The filament voltage is applied across the prong terminals of the filament in the tube base and the current flowing in the filament heats it to the electron-emitting temperature.

In the indirectly-heated tubes, the cathode-heater arrangement may be one or the other as shown in Fig. 6-2. The cathode is a sleeve which is insulated from the heater wires but surrounds them. Upon this sleeve are baked a number of layers of an oxide coating that freely emits electrons. The heat from the heater raises the temperature of the cathode sleeve to the emitting value. The essential advantage of this type of emitter over the directly-heated type is that it permits heater operation on alternating-current power circuits. The cathode material cannot follow the rapid variations of the heater current, which

A special kind of diode should be mentioned here, because experiments with it are quite interesting. It is the *noise diode*, intended for the specific purpose of producing wide-band RF noise through the *shot effect*. Shot effect noise is fluctuations in the anode current due to the random collection of electrons. We have already mentioned that the anode current is controlled by the space charge around the filament. It was discovered, to some surprise, that this correlated successive electrons so that they were emitted regularly to maintain a constant current, and therefore the shot effect was nearly completely eliminated. That is, a normal diode has no shot effect noise in its plate current.

The noise diode is designed so that at reasonable plate voltages, all electrons emitted by the filament are immediately drawn to the plate without forming much of a space charge. Since the electrons are emitted randomly, the anode current will show the full shot effect noise. This is done by purposely making the filament to have low emission. To do this, a tungsten filament is used. Noise diodes give us the opportunity to observe a tungsten filament, as well as temperature saturation.



An available noise diode is the 5722, whose basing is shown at the right. The 7-pin miniature tube was made as late as 1977, and now costs about $14, which is probably not much more than when it was new. The maximum plate voltage is given as 200 V, and the maximum plate current as 35 mA, so apparently the plate can dissipate 7 W. The plate has wings that make a good dissipation probable.

A circuit for testing the 5722 is shown at the left. Note that an RF choke is put in the plate lead to act as a load for the current fluctuations. This choke should be rated for the plate current employed. I connected a variable DC supply to the filament as shown, to pins 3 and 4, leaving the center tap alone. This supply

2, 7 and 9. This tube is designed for the rugged service of a television *damper diode*. During horizontal retrace, the damper diode conducts, charging the boost capacitor while absorbing the large inductive kick. The peak inverse voltage is 6000 V, the peak current 800 mA, and the average current 135 mA. The large-diameter cathode tube and long plate imply a large perveance, which, in fact, is about 2.3 $mA/V^{1.5}$. This tube happens to be very cheap, but would serve as an excellent half-wave rectifier for practically any purpose. There are other damper diodes, such as the 6W4 and the 6AX4GT (perveance 1.42), that would have similar characteristics.

As an example of the small signal diodes that are often combined with a triode or pentode in the same envelope, and share the same cathode, the 6AV6 or 6AT6 furnish good examples. The 6AV6 has its heater at pins 3-4, cathode at pin 2, and the signal diode plates at pins 5 and 6. The maximum current for each diode is 1 mA. I connected the two plates together for measurement, and took the current up to 3 mA, for which a plate voltage of 6.4 V was required. The curve of I against $V^{1.5}$ sagged a little at low currents, but the upper part was quite linear, showing a perveance of 0.085 $mA/V^{1.5}$ for one plate. The incremental resistance was 4.55kΩ, and V/I was 5.05kΩ at 1 mA. The current for one plate obeyed the formula $I = 0.15 + 0.085V^{1.5}$ mA. In this tube (and similar ones) the plates are flat, one on each side of the cathode.

The 1A3 seems to be the smallest signal diode of all. It was designed for portable measuring apparatus. The heater takes 0.15A at 1.4V (a D cell), connected to pins 1 and 7 of the 7-pin miniature envelope. The cathode is at pin 3, the anode at pins 2 and 6. The peak inverse voltage is 330V max., the maximum plate current 5 mA, and the average plate current 0.5 mA DC. Maximum heater-cathode potential is 140V. The anode is only a few millimeters high; most of the envelope contains only vacuum. The measured perveance was 0.075 $mA/V^{1.5}$.

The Noise Diode

therefore has very little effect upon the instantaneous temperature of the cathode. Hence a steady rate of emission can be maintained by the cathode with a uniform distribution of emission along its entire surface, despite the fact that the current through the heater varies periodically.

Furthermore, if the cathode is surrounded by a charged surface, there is a uniform distribution of the lines of force between the charged

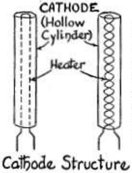
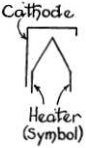


FIG. 6-2 (left). In an indirectly heated cathode, the heater wire is usually either U-shaped, as shown on the left, or it may be twisted throughout its length. The heater wire is enclosed within the electron emitting cylinder.
FIG. 6-3 (right). The symbol of the heater and cathode of a vacuum tube that is used in schematics is an inverted V under an inverted L.



body and the cathode along its entire length, because all of the cathode is at the same potential with respect to the surrounding charged surface. In some instances the heater wire within the cathode sleeve is an inverted U, whereas in other cases the heater is twisted throughout its length, as shown in Fig. 6-2.

When a cathode heater system is shown in an electrical wiring diagram, it appears as in Fig. 6-3, an inverted L over an inverted V. Since in the normal electrical system, the heater circuit is of little importance with respect to the other components associated with the performance of the circuit, it is often omitted from the schematic symbol, it being assumed that a simple reference upon the diagram is sufficient to indicate the method of connecting the tube heaters to the heater-current supply system. That shall generally be our practice, for once you understand the function of the heater and its behaviour under different conditions, there is little need for further discussion.

As to the plate or anode, its schematic representation is a short straight line, which may be located parallel to the vertical portion of the cathode, as shown in Fig. 6-4(A), or it may be parallel to the horizontal part of the cathode, as shown in Fig. 6-4(B). In the case of the filament-type tubes the plate is shown as in Fig. 6-4(C) and (D), being vertical or located above the filament. This is merely a matter of individual preference on the part of the person making the drawing.

A circle generally surrounds these elements to show that they are in an evacuated envelope. Generally the symbol for the heater is omitted in schematic drawings as this circuit is unessential to the functioning

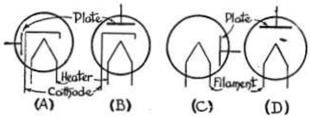
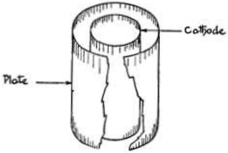


FIG. 6-4. The line indicating the plate may be drawn in any one of the four positions shown in the above schematic symbols of a diode.

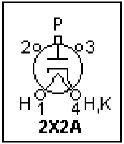
of the other elements of the tube. Concerning the specific arrangement of emitter and plate within the actual tubes, the most general form of construction is to have the plate surround the entire cathode, as shown in Fig. 6-5.

FIG. 6-5. The cylindrical plate surrounds the cathode in the actual diode, as indicated on the right. These two electrodes are supported by wires that are embedded in the glass press at the bottom of the tube.



In connection with the actual construction of diodes, some employ two diodes located within a single envelope. In some, those of the indirectly heated variety, individual cathodes are available for each section. In other tubes, which use a filament as the emitter, two separate plates are available, and the two separate filaments are connected in series. Illustrations of these are given in Figs. 6-6(A) and (B) together with the schematic symbols. The tube which contains separate cathodes for each plate is known as a *duo-diode* (for example, the 6H6 G), whereas the tube which uses a common filament for the two plates is usually called a *full-wave rectifier* (for example, the 80).

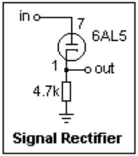
The 7Y4 is a typical small full-wave rectifier with an indirectly-heated cathode, like the more common 6X4 (miniature) and 6X5 (octal). This "Loktal" tube is inexpensive. Many of the common rectifier diodes are rather costly, for the curious reasons associated with the current tube market. The heater, taking 6.3V at 0.5A, is connected to pins 1-8 (as with all Loktal tubes). The cathode is pin 7, and the plates are pins 3 and 6. The peak inverse voltage is 1250 V, the peak current 180 mA, and the average dc current 70 mA. The heater-cathode voltage should not exceed 450 V. Measure the plate voltage for currents up to, say, 50 mA, and plot the results as for the 6H6. Again, we find a straight line and a perveance of 0.58 mA/$V^{1.5}$. Note that the plate voltage varies considerably as the current changes, from 4 V at 7 mA, to 16 V at 40 mA. Compare these voltages with those for a mercury-vapor *phanotron* as discussed in the next section. The 7Z4 is a somewhat larger full-wave rectifier (with perveance 0.40), the Loktal equivalent to the types 80 or 5Y3 that are now much more expensive.



An excellent diode for observing the Langmuir-Child law is the 2X2A. This tube has a 4-pin base like the 82 phanotron discussed below, and the large, bell-like anode is brought out to a cap at the top of the ST envelope. The oxide-coated cathode thimble is easily seen. The heater takes 2.5V at 1.75A, so it can use the same transformer as the type 82. The rated DC current is 7.5 mA, and the maximum voltage is 4500V. A plate voltage of about 60V is needed to reach 7.5 mA plate current, so measurements can be made over a wide range of voltages. Plot your results as $I^{2/3}$ vs. V. A straight line will be found, that intercepts the V axis at -1.2V. The perveance of the 2X2 is found to be 0.0165 mA/$V^{3/2}$. The unusually low value is due to the large cathode-anode spacing.

The 6V3-A is a strange miniature tube with a cap on top that is the cathode connection. Its heater, connected to pins 4 and 5 of the 9-pin miniature base, takes 1.75 A at 6.3 V. The plate is connected to pins

V can be resisted, and the DC plate current should not exceed 9 mA. Peak currents can go up to 45 mA if necessary, however. I measured the perveance as 2.42 mA/$V^{1.5}$, for one plate, a large value. The 6AL5 gives 9 mA with a plate voltage of only about 2.5 V! The heater, connected to H-H, pins 3 and 4, takes 0.3 A at 6.3 V.



Try the 6AL5 in the circuit shown at the left, which is a basic signal rectifier with a 4.7k load resistor. Feed it with the signal generator, and compare the output and input with the oscilloscope. Try input peak-to-peak voltages of only 2 V or so. You will notice that there is no "diode drop" with the 6AL5--it acts like a perfect diode, rectifying down to small voltages. We know how to do this with a semiconductor diode and an op-amp, but here it's done quite simply. The 6AL5 has an incremental resistance of only about 237 Ω, and is nearly linear. It is easy to run a plate voltage versus plate current curve with a low-voltage power supply. Keep the load resistor, and subtract the voltages at plate and cathode to find the plate voltage.

The 6H6 is an octal dual signal diode like the 6AL5, in a unique small metal envelope. The heater is connected to pins 2-7, the cathodes to 4 and 8, the plates to 3 and 5. 3 and 4 are one diode, 8 and 5 the other, and completely independent. It can be used for any reasonable service, such as AM detection, as a full-wave rectifier, or as a voltage doubler, so long as the current per plate is 8 mA or lower, and inverse voltages do not exceed 420 V. The voltage between heater and cathodes should not exceed 330 V. Measure the plate current as a function of the plate voltage up to 10 mA (the plate voltage will be about 7 V), and plot the current against the 3/2 power of the voltage. I obtained a rather straight line, showing agreement with Langmuir-Child, with a permeance of 0.5 mA/$V^{1.5}$. At 8 mA, the incremental resistance was 590Ω, and V/I = 785Ω. The 12H6 and 7H6 are similar tubes with different heater ratings and basing.

The justification for such a distinction between the two tubes is due solely to construction and not utility, for the duo-diode can be arranged for use as a full-wave rectifier without any trouble. However, the fact that separate cathodes are available in the duo-diode gives it certain operating capabilities which are not possessed by the tube which has the two separate plates, but a single source of electrons. In the case of the duo-diode, there may be only a single heater winding serving the two cathodes.

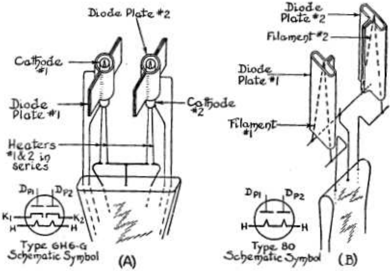


FIG. 6-6. The duo-diode tube shown in (A) has a cathode for each of its two plates and the 80 type rectifier shown in (B) has but a single continuous filament for both of its two plates.

The presence of more than one diode structure in an envelope does not in any way alter the considerations surrounding the basic two-element tube, and this applies equally well to the tube with the two plates but a single filament. Whatever is said about the single diode applies equally well to the other section. The same is true if the two plates of the two diodes are connected in parallel by some electrical connection and two cathodes are operated as one. The only difference resulting from such an arrangement is a change in the characteristics of the tube, but not in the basic principles of operation. Just what we mean by this in actual numerical values will be shown later in this chapter.

Function of the Diode

The main function of the two-element tube is as a *converter of power*. By this we mean that it is a device whereby electrical power in the form of alternating voltage and current can be converted into electrical power in the form of pulsating direct current, and subsequently to d-c voltage. This is the process of *rectification*. From the viewpoint of application, this description includes a very great number of different operations. In the field of communications alone, the various ways in which such power conversion is utilized are very numerous.

The principles governing the process of rectification in diodes have already been described, although it is true that when they were discussed we deliberately omitted mentioning the association between the phenomenon then considered and rectification.

You will recall mention in Chapter 4 that electrons moved from cathode to plate only when the plate was maintained positive with respect to the cathode. When the plate was made negative with respect to the cathode, current flow in the diode ceased.

Therein lies the process of rectification in the diode, for if we apply an alternating voltage between the plate and the cathode of a diode, current will flow through the tube, hence through any system connected to the tube—in a series of pulses corresponding to the periods when the plate is positive with respect to the cathode. This output current and corresponding voltage is unidirectional.

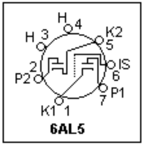
If we now view the vacuum tube as a conductor, it is evident that *the tube can conduct current in only one direction:* from the emitter to the plate. Therefore, we are justified in saying that the diode possesses the property of *unilateral conductivity*. If for the moment you were to visualize something which periodically makes the plate alternately positive and negative with respect to the emitter, and also remember the laws which govern the motion of electrons between charged bodies, you can then readily visualize the flow of plate current as a series of pulses—a pulse of current each time that the plate is made positive with respect to the cathode, and no current flow when the plate is made negative with respect to the cathode. In brief, this is the process of rectification of an alternating current into a pulsating direct current or the conversion of a-c power into d-c power. We shall discuss this in more detail later.

Electron Flow and Current Flow

Before we can continue any further discussion of current flow in

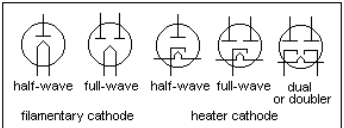
and other interesting things. They do work rather well, and it is good to make their acquaintance.

The forward voltage (in the direction of current flow) of a diode is always relatively low, less than 15 V or so. The plate current is roughly proportional to the 3/2 power of the anode-cathode voltage (Langmuir-Child law), and the proportionality factor is called the *perveance*. The perveance depends on the geometry of the tube, increasing with larger area and closer spacing. It's remarkable that most diodes agree with Langmuir-Childs so well, in spite of different geometries. Since the voltages are low, contact potentials may affect your measurements. Contact potentials are discussed below in the section on low-voltage tubes. The easiest way to find the perveance is to plot $I^{2/3}$ against V, and to draw the best straight line. The intercept gives the value of the "true" zero plate voltage, and the slope, raised to the 3/2 power, is the perveance. Perveances range from 0.02 to 2.4 $mA/V^{3/2}$ for a representative assortment of 12 diodes of all types. There is no turn-on voltage drop for a thermionic diode, as there is for a silicon diode. Conduction begins immediately when the plate is positive with respect to the cathode, and stops immediately when the plate goes negative. It is easy to measure the V-I characteristic of a diode with a low-voltage DC supply, a voltmeter and an ammeter. I use a 100Ω resistor in series to make adjustment easier and safer. Thermionic diodes are not as easy to destroy as semiconductor diodes, and will take a good deal of abuse.



The 6AL5 dual diode, whose basing is shown at the right (7-pin miniature socket), is a typical signal diode. IS is an internal shield between the diodes. The two diodes and the shield are easily seen through the glass envelope, and you should notice how close the plates are to the cathodes. The close spacing means a large perveance, so only small plate voltages are required. Don't connect this tube directly across high voltages! A peak inverse voltage of 330

Thermionic diodes, like semiconductor diodes, are divided into *signal* diodes that handle small currents at low voltages, and *rectifier* diodes that handle large currents, often with large inverse voltages. A diode has an electron-emitting cathode and an electron-receiving anode or plate. The arrangments of cathodes and plates in commercial tubes, and what they are called, are shown in the figure. Signal diodes are also often added to a triode or pentode, sharing the same cathode and with one or two plates. Current flows only from plate to cathode, and this unidirectional conduction is the purpose of a diode. Diodes cannot amplify.



Types of Thermionic Diodes

Signal diodes always have indirectly-heated cathodes, so they are easy to use. It is only necessary to make sure that the heater-cathode voltage does not exceed specified limits, usually a few hundred volts. Rectifier diodes often have filamentary oxide-coated cathodes, since these cathodes are more efficient when large currents are needed, requiring less power. We are considering only vacuum diodes, *kenotrons*, in this section. Thermionic gas diodes, or *phanotrons*, will be treated below, since they have rather different properties.

Thermionic diodes have now been completely superseded by semiconductor diodes, largely for economic reasons, physical size and the need for a filament supply. A silicon diode capable of carrying 1 A is available for $0.04 or so, and takes up very little room. However, diodes can teach us a lot about thermionic emission

the diode, one important point must be mentioned. It is important not only in connection with the diode, but with regard to all other tubes. We are referring to the modern conception of current flow in the vacuum tube based on the electronic viewpoint versus the old conception of electric current flow which is still prevalent in vacuum-tube discussions.

In view of all that we have said so far, particularly in Chapter 4, you naturally conclude that since the movement of electrons is from the emitter to the plate within the vacuum tube, and since the movement of electrons constitute electric current, the electric current flow within a vacuum tube (plate current) is from the cathode to the plate or from minus to plus. The movement of this current outside of the tube is from the plate to the cathode through whatever devices are connected between the plate and cathode.

That impression is entirely correct, yet we find it necessary to speak about another and contrary one. Frankly, we do not like to mention it, let alone discuss it, but it is about time that this old-fashioned and erroneous idea was completely cast out of text books. However, since so many authors still use it in their illustrations, we find it necessary to recognize that it existed at one time.

Back in the dim dawn of electrical knowledge, nothing was known of electrons nor of our present conception of the atomic make-up of matter. It was, however, necessary to specify the direction in which electricity flowed and so, quite arbitrarily, it was decided to say that electric current flowed from the positive pole of the battery to the negative pole of the battery through the external circuit. Today, however, we know that *electrons flow from the negative pole of the battery, through the external circuit, and back to the positive pole of the battery.*

As you can see, our modern idea is exactly opposite to the old one, but the old conception was universally adopted and has been in use for a long time. The result is that in many illustrations, in fact, most illustrations of current flow in vacuum-tube circuits, the current is shown as flowing from the plate to the emitter within the tube, and from the plus terminal of a battery or voltage source to the minus terminal of the voltage source through the external circuit. In order to be in line with modern thought, a schematic diagram founded upon the modern concept of electron flow should be shown, wherein the electrons flow from the emitter to the plate and the current flows from the negative pole of the battery to the positive pole of the battery through the external circuit.

We, too, are guilty of the practice of illustrating the old convention, but this is where we stop. We show but one schematic of the old convention and everything else is in line with the new. In other words, all of our drawings indicating movement of current in vacuum-tube circuits will conform with the modern concept of electron flow. Consequently, the direction of electric current flow in vacuum-tube circuits as shown in this book, may differ from illustrations shown in other vacuum-tube texts although the relative polarities will be the same in all illustrations. For you see that changing the direction of current flow from the old to the new concept does not change the polarity of points along the current-carrying circuits.

The reason why the relative polarities do not change when changing from the old to the new convention is because that point in the old convention which was declared as being positive, since the current left from that point, is now declared as being positive in the new convention because the current arrives there. Thus, while the direction of current flow is changed, *the polarities remain as before.*

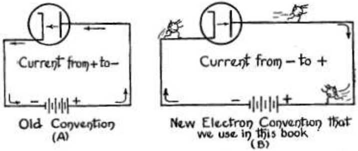


FIG. 6-7. The old convention of current flowing from + to — is illustrated in (A) and the modern convention of current flowing from — to + is shown in (B).

An example of the old and new conceptions of current flow are shown in Figs. 6-7(A) and 6-7(B). From now on we shall forget all about the old convention.

Plate Current in The Diode

Once again we shall discuss the flow of plate current in the diode tube, but this time we shall interest ourselves in the factors which determine the magnitude of this current, rather than in what makes it flow through the tube and through the external circuit. The basic

A tube designated simply 6N7 will be a metal-envelope octal tube with a 6.3V heater. A 6N7GT will have a cylindrical glass envelope. A 6N7G would have a shouldered glass envelope of the graceful shape designated ST. The electrical characteristics of such tubes were the same, whatever the envelope shape.

A very important part of vacuum-tube technology was bringing the metal leads through the glass envelope. Coefficients of expansion must be exactly matched, and the seal must be strong. Originally, tubes had bases (usually Bakelite) to support the contact pins mechanically, taking the strain off the pressed-glass seal, which was made of lead glass. Around 1935, the metal envelope was developed, but there was still a base. The all-glass "miniature" tube was made possible by the "button seal" that supported the contact pins mechanically as well as bringing them through the glass, allowing the base to be eliminated and tube size to be reduced. The insides, or "cage," was the same size as in previous tubes, however. It is supported on its leads, which are welded to the contact pins before the envelope is fused in place and evacuated. The button seal is also used, in a larger form, on tubes designated by GB at the end of the type designation, and by Loktals. The final step in manufacture was "flashing" the getter, usually barium or magnesium, to perfect the vacuum by adsorption of any remaining gases, leaving a shiny coating. This was generally done by heating a loop inductively by RF from outside.

7, and often to pins 3-4 on 7-pin, or 4-5 on 9-pin, miniature tubes. Sometimes halves of the heater can be connected in series or parallel, for two different voltages. Sockets were originally mounted in holes punched in aluminum chassis, secured by locking rings or by screws and nuts with a mounting plate. The chassis was, not surprisingly, the ground or common.

The "Loktal" tube was an excellent idea that was never universally adopted, mainly because miniature tubes took over in the 1950's. Since loktal was a trade name, RCA used "lock-in" instead, and you sometimes see "loctal." The loktal tube has an 8-pin button-seal (like the seal on miniature and octal GTB tubes). A natural metal base (of some aluminum alloy, apparently) shields the base of the tube and has a central pin with a circumferential locking groove. The pins project only 6 mm, and are 1.4 mm in diameter, much smaller than octal pins, so the locking action guarantees that the tube will stay in the socket in spite of the small pins. The tubes are roughly the same size as an octal GT tube. Most are one size, but a few power tubes have a slightly longer envelope. There are no grid caps on any Loktal tube, and the heater connections are always to pins 1 and 8. Among the thoughtful features of loktal design, the type number appears in a hexagon on the top of the tube where it is visible from above, not on the side as on octal tubes. There is a dimple on the base corresponding to the key of the central pin, making the tube easy to orient for insertion. It seems that a lot of getter was used, so the tops of the envelope appear heavily silvered. The available types are only those used in AM and FM receivers. There are, nevertheless, enough types for a broad variety of experiments, and the prices are not excessive, so you may want to standardize on Loktals. Type numbers beginning with 7 have 6.3 V heaters, while type numbers beginning with 14 have 12.6 V heaters. There are some 7xx and 14xx tubes that are not Loktal, and some tubes that actually take a 7 V heater supply. One loktal rectifier, the 5AZ4 (a 5Y3 equivalent), has a 5 V filament. Loktal tubes designed specifically for battery-powered equipment had 1.4V filaments. The type numbers began with "1L." There were also rectifier and beam power loktals with 35, 50 and 70-volt heaters for AC/DC sets with series heater connections.

reasons for the flow of current between the elements of the tube have already been discussed in Chapter 4, so that we need merely illustrate the similarity between the diode and the two-element structures previously illustrated. This is done in Figs. 6-8(A), (B), and (C). Since we shall speak about the flow of current through the circuit, a meter M is included in each illustration.

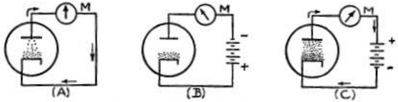


FIG. 6-8. High-speed electrons arriving at the plate form a small plate current, even though no potential is applied to the plate; this is shown in (A). No plate current results when the potential on the plate is negative, as shown in (B), and a current flows that is greater than that of (A) when a positive potential is applied to the plate; this is shown in (C).

In each of these illustrations, the cathode is the equivalent of the emitter discussed in Chapter 4, and the plate is the equivalent of the positively charged surface. The battery shown in Fig. 6-8(C) is the voltage source used in Chapter 4 which made the charged surface positive with respect to the plate. In the case of Fig. 6-8(B), the battery makes the plate negative with respect to the cathode.

The dots shown between the cathode and the plate in Figs. 6-8(A), 6-8(B), and 6-8(C), correspond to the space charge discussed in Chapter 4. In Fig. 6-8(C), the plate voltage is of such magnitude that a flow of plate current occurs. In Fig. 6-8(B), the plate having been made negative with respect to the cathode, the plate current is zero, and the space charge can be seen concentrated in the neighborhood of the cathode just as described in Chapter 4.

We now come to Fig. 6-8(A), which has not been mentioned. Basically, the conditions existing in this circuit correspond to what has been described in Chapter 4 but, as you can see, the battery has been omitted and the plate is joined to the cathode. What happens in this circuit? In the first place, since the plate and the cathode are joined and no voltage source is connected between the plate and cathode, presumably no difference of potential exists between these two elements. Since the two are joined, whatever the voltage may be at the cathode—incidentally, this is assumed to be zero—the same potential is supposed to exist at the plate; hence the plate is not exerting any attracting force upon the electrons in the space charge.

But the meter indicates the flow of a very small amount of current! This is not as mysterious as it may seem at first thought. In fact the answer has already been given, but since it may have been lost in the maze of other subject matter, repetition is justified. In fact, it is worthwhile to give this subject somewhat more thought inasmuch as it plays a very important role in the application of the diode tube in many systems.

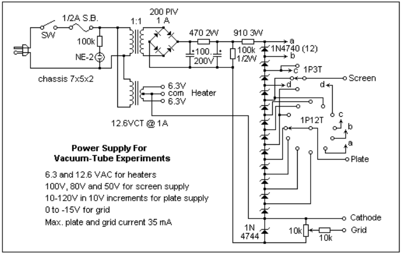
Contact Potential

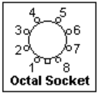
You may remember, while discussing the velocity with which the electron leaves the emitter, that we made the statement that these speeds varied; some electrons left the emitter at a very slow speed, whereas others left the emitter with a high velocity. In fact, we said that the speed of some electrons emitted during each unit of time was so great that they could penetrate right through the space charge and travel over to the plate without any attracting force existing at the plate, that is, without any positive voltage being applied to the plate, and hence with no electrostatic field set up by the plate.

It is these high-speed electrons which reach the plate and constitute a plate-current flow through the diode, and a corresponding movement of electrons through the external circuit. This current is indicated upon the meter.

This condition of plate-current flow through a diode without any electrostatic field being set up by the plate, is a very important one as far as practical operation is concerned. It means that a value of zero voltage upon the plate does not necessarily signify zero plate current. It is necessary to find a term which will express the *equivalent* voltage difference which can be imagined to exist between the plate and the cathode, and which is responsible for the flow of this amount of current. For, there is not supposed to be any voltage difference between the cathode and the plate since the cathode is a unipotential surface, and joining the plate and cathode in such a manner is supposed to place both at the same potential all along both surfaces.

Yet we know that current does flow in the circuit and, if we assume that the external circuit joining the cathode and the plate has resistance—which is a normal assumption—a voltage drop due to this flow of current can be expected to exist across this resistance. This voltage does exist and the higher the resistance of the external circuit which





Vacuum tubes come with metal or glass envelopes, and in latter days with either the familiar octal arrangment of 8 pins, or as miniature glass tubes with 7 or 9 pins. There were earlier bases with four, five or six pins. Later, 12-pin miniature "compactron" or "duodecal" tubes were used in TV sets. Miniature tubes were not miniature, simply tubes with a button seal and all-glass envelope closely fitting a normal-sized cage. Subminiature tubes were actually miniature. Sometimes connections to grid, plate or (rarely) cathode were made to caps at the top of the tubes. In small tubes, these caps have a diameter of 1/4". The pins are numbered consectively clockwise, starting from the left of the index key for the octal, or to the left of the wider space, for the miniature, always looking at the bottom of the tube. This is shown for the octal base at the left. Pin numbers are given in the circuit schematics here. Most sockets have pin numbers marked. You will need to get sockets for the tubes you study, one for each type of socket. Solder wires to the tab at each pin that can be inserted in the solderless breadboard. I use the resistor color code for the pin numbers. A convenient octal socket fixture is available that comes with screw terminals for making connections. It was intended for relays, but is very useful for tube experiments. Heater connections for octal tubes are typically (not always!) to pins 2 and put in a box with an on-off switch and convenient terminals. Ground the heater supply (at a center tap if one is provided) to the B+ ground, to avoid excess voltages between heater and cathode. If you have a 12.6V CT (center-tapped) secondary, you can supply both 6.3 and 12.6 V heaters. Many 12.6V miniature tubes can also be connected for 6.3V. Tubes whose designations begin with "1" have filaments that can be supplied from a single D cell. Obtain a holder for the cell so connections are easy. 6.3 V was chosen to be compatible with 6 V car batteries, but the supply is usually AC. Many rectifier diodes use a 5 V filament or heater supply, apparently for historical reasons.

A "C" supply, for the grid bias in measuring characteristics, can be any isolated low-voltage supply of say, 15V, and a potentiometer can be used to pick off a variable voltage, since little current is involved. A separate high-voltage supply for screen grids may also be convenient, though it is easy to pick off the necessary voltages with a Zener or a VR tube from the main B+ supply. This cannot be done, of course, if the B+ voltage is adjusted using a variable transformer.

An all-in-one economical supply for vacuum-tube measurements is shown below. It uses an inexpensive isolation transformer from All Electronics, and can be made for about $30.00. The most expensive single part is the aluminum chassis. The grid potentiometer could be a precision 10-turn pot, but this would be expensive, and an ordinary carbon or plastic potentiometer (1/2 W or better) will be satisfactory. The maximum plate voltage of 120V and maximum plate current of 35 mA is adequate for many measurements. If you use a three-wire line cord, ground the chassis to the green wire. If you use only a two-wire line cord, it is probably better not to ground the chassis.

connects the plate to the cathode, the more easily it can be measured. As to just what you would call this voltage, the best that we can do is to refer to the name by which it is known, namely, *"contact potential."*

The use of this term to identify this voltage is not wholly correct, yet, for want of a better name, it is used in commercial tube literature, and we shall therefore use it on those grounds.

Determination of Diode Behaviour

All of this information about the flow of current in a diode, with a positive, a negative, and zero voltage at the plate, merely supplements the facts given in Chapter. 4. What we wish to determine is the behaviour of the diode when those conditions which cause the flow of plate current are varied. Only then can we establish facts relative to the manner in which the diode is used.

What are the conditions which determine the amount of plate-current flow in the diode? Since the magnitude of plate current is partly dependent upon the emission of electrons from the cathode or filament of the tube, the temperature of the emitter is a factor. In accordance with what was said in Chapter 4, the electrostatic field set up at the plate influences the effectiveness of the space charge, and hence affects the plate current. Consequently, we see that the value of the plate voltage has an effect upon the amount of plate current flowing through the tube.

We must therefore establish characteristic curves, or behaviour curves, showing the variation in plate current with emitter temperature and also characteristic curves showing the variation in plate current with plate voltage. These are the two basic characteristic curves of the diode, although, strange as it may seem, that which can be considered the more basic, namely, the emitter temperature—plate current characteristic curve, is infrequently used. In fact, tube manufacturers do not usually show such curves in their tube specifications, the reason being that tubes are designed to be used at a specific value of emitter temperature, as determined by the voltage applied across the filament or heater.

Emitter Temperature—Plate Current Characteristic

To establish the manner in which the plate current of the diode varies with the emitter temperature, it is necessary to set up a circuit using a diode wherein it is possible to create various emitter temperatures and to maintain the voltage applied to the plate at a constant value. The general shape of this curve can be predicted from what has already been said about the various conditions of emission.

First of all, we know that electron emission from metals, such as are used as emitters in vacuum tubes, requires a definite high temperature. In addition, we know that raising the temperature of the emitter will increase the amount of emission; however, because of the presence of the space charge within the tube, increasing the emission from the emitter does not necessarily mean that a greater number of electrons will travel over to the plate of the tube.

We have further learned that the flow of plate current (electrons) across the inter-electrode space, between the two surfaces of the diode, depends upon the relative magnitudes of the fields due to the space charge and the field set up by the plate when the plate is made positive with respect to the emitter. Under the circumstances, it would seem natural that a curve of plate current versus emitter temperature with a fixed plate voltage, would start at zero, rise, and then eventually flatten out at some value, beyond which there would be no further increase in plate current no matter how high the emitter temperature.

For example, with a fixed plate voltage of reasonable value, emission would start when an emitting temperature was reached. In this connection we are assuming that the temperature of the emitter is just high enough to cause sufficient emission, and a plate current which would be indicated upon a reasonably sensitive meter. At this point the space charge would be of negligible effect in offsetting the field due to the voltage upon the plate so that there is a progressive movement of the emitted electrons through the space charge to the plate.

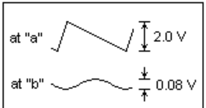
As the temperature is raised, the emission would increase and, while the number of electrons located in the space between the emitter and the plate would also be increased, the field due to the plate voltage would still be capable of sufficiently nullifying the field due to the space charge, so that all of the electrons emitted would move over to the plate.

This condition would continue with further increases in emitter temperature and the plate current would also continue to increase. However, after a while when the emitter temperature has been raised to a sufficiently high level, the field due to the space charge would begin to offset the field which is due to the positive voltage upon the plate. Then the rise in plate current, for equal increases in emitter temperature, would no longer be as great as it was before, and the plate current curve would begin to level out.

The point where it would flatten would be that which is equivalent to the creation of a space charge which would have a field sufficiently

satisfactory for anything but power amplifiers. If supplied from a variable transformer, it becomes a variable supply for all voltages from 0 to 300. Note very carefully that one side of the supply is connected to the AC line, and this must be the grounded side, for your safety, and to avoid ground loops. You cannot ground the positive terminal of this supply to get a negative voltage supply (for use as a C supply, for instance). An isolation transformer, if you have one, would eliminate this hazard. If you don't have an isolation transformer, use a polarized plug to guarantee that the white wire is connected to the circuit ground. If you have a good ground, consider the old trick of connecting only one wire in the power cord, and using the ground to complete the circuit. It is best to observe the power ratings of the resistors and the voltage ratings of the capacitors. This circuit has been tested, except for the fuse. If the 0.5A slow-blow fuse fails, try a 1.0A. This fuse is to turn things off if a capacitor fails; nothing valuable is protected here, but it saves mess.

The RC ripple filter is worth the expense. Waveforms are shown at the left. The waveform at node "a" is the familiar one for a "tank" capacitor, and the ripple is fairly large. Since the impedance of a 100 μF capacitor is only 26Ω at 60 Hz, the ripple is reduced by a factor of almost 25. At 300V output and a load of 12 mA, the ripple is less than 0.1V, a very satisfactory result. Note that all that is left in the ripple is the 60 Hz component. The filter would work even better on a full-wave rectifier, but here it is very satisfactory, better and more economical than larger capacitors. Of course, a filter choke could be used for an even better result and less voltage drop, but this would double the cost of the supply.

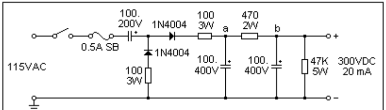


Effect of Ripple Filter

You will also need a heater transformer, which can be quite small if supplying only one tube that requires 0.3A. The transformer can be loads, should not be used, since they are autotransformers and do not provide isolation. They are, in fact, quite dangerous things, and should be used with great care. The supply was built in a 5" x 7" x 3" aluminum box, with an octal socket for the VR tube on top. The socket can be left vacant when the fixed voltage output is not required.

The voltage regulator requires a certain minimum current (about 5 mA) to function properly. If you are only drawing a few milliamperes from the supply, connect a 12k bleeder resistor across the output. Otherwise, the regulator will not adjust down to the lower voltages. Or, 220Ω and 10k fixed resistors, and a 15k pot, could be used at the voltage regulator, which would draw the necessary minimum current. The VR tube can be replaced by a high-voltage Zener diode.

A 25W isolation transformer is available at the date of writing from All Electronics (See the Your Laboratory page for a link) for $4.50. This transformer is surplus from the Power One firm, and is an excellent value. Solder a jumper between tabs 1 and 3, and another between tabs 2 and 4. The 120V input is connected between 1-3 and 2-4. The output tabs are marked B. This transformer would work well in the circuit above, or it could be put in a box and wired with line cord and output receptacle as a general isolation transformer. It should supply 200 mA without trouble, ample for our purposes.



Voltage-Doubler B+ Supply

An idea for an inexpensive B+ supply is shown at the right. The greatest expense is for the capacitors, which will cost about $15. It is based on a half-wave voltage doubler, and gives 300V for a 115V rms input. It cannot supply large currents, but is perfectly

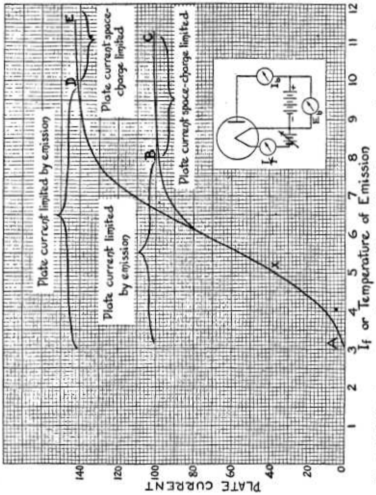


FIG. 6-9. Emitter temperature—plate current characteristic. These curves show that the plate current does not increase appreciably above a certain value even though the temperature of the emitter is increased.

great to offset at the emitter any attracting force which the field, due to the voltage applied to the plate, would have. From this point on, there would be a steady flow of plate current, the magnitude of which would be space-charge-limited and there would be no further increase in plate current for a further rise in emitter temperature.

Such a curve is *ABC* of Fig. 6-9, and which is made by using the accompanying electrical circuit. Although we have described this curve in terms of emitter temperature, it is more customary to plot such curves in terms of either filament or heater current indicated upon the meter "I_f". The horizontal axis of the graph can be designated in either filament current or in emitter temperature. The vertical axis is marked off in values of plate current. Inasmuch as nothing is gained by giving specific values of either filament or plate current, the values shown are arbitrary. The meter marked "E_b" is used to indicate the plate voltage, while the meter "I_b" is used to measure the plate current.

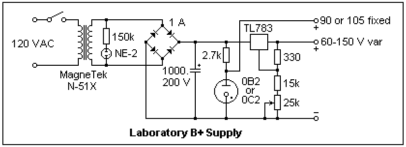
Referring again to this emitter temperature—plate current characteristic, the point *B* represents the saturation of the emitter for the existing plate voltage. It is evident from this characteristic curve that nothing is gained by increasing the temperature of the emitter or the filament (heater) current beyond that point along the horizontal axis which is equivalent to the point *B* on the characteristic, because there is no further increase in plate current. All emission greater than that productive of point *B* on the plate-current curve is excess. All the electrons emitted in excess of those which progressively advance to the plate are being repelled back into the emitter.

The means of utilizing higher emitter temperature than that corresponding to point *B* in the curve *ABC*, is self evident. Since the point *B* on curve *ABC* is due to the action of the space charge, the means of raising this point is by reducing the effectiveness of the space charge. To do this the field set up by the voltage upon the plate must be increased, which is done by the simple expedient of raising the voltage applied to the plate.

When this is done the rising portion of the plate-current curve is increased and a new value for temperature saturation or the start of the space-charge-limited plate current, is established. This is shown as curve *ADE*. Whereas with the lower value of plate voltage the amount of emission corresponding to point *B* at approximately 8 units on the temperature axis represented temperature saturation, with the higher value of plate voltage, more electrons were attracted to the plate and the space charge was not limiting the plate current. It was necessary to advance the emitter or temperature to 10 units before the

well. All the usual resistors and potentiometers are not afraid of 150V, so long as power ratings are observed. 1W and 1/2W resistors may be required in some places. Capacitors must be able to stand the voltages across them; many of those used with transistors will not be adequate. Keep a separate kit of capacitors rated at 100 V and above for this work. High-voltage capacitors are not needed everywhere, only in the plate circuits and for coupling from plate circuits.

The circuit of the laboratory B+ supply that I use for vacuum tubes is shown at the right, and the supply itself is shown in the photograph



below. It provides a regulated variable 60-150 V output, and a regulated fixed voltage output (for screen supply) created by a VR tube. VR tubes can be exchanged for different voltages. The MagneTek N-51X 115 V-115 V isolation transformer is available

from Antique Electronics (see references), and a cheaper one from All Electronics. The transformer secondary has a DC resistance of 22Ω, which limits the surge current satisfactorily without having to add a series resistor. By no means eliminate the isolation transformer and use the 120 V household supply directly, because of the ground hazard. A variable transformer (Variac) is an *autotransformer* that does not isolate the output from the power line ground. I earnestly recommend that you do not work on AC circuits without isolating them from the service ground. The 110/220 adapters commonly available in 50W and 300W sizes, used for shavers and other small through the discharge in the "normal glow" region, in which the glow does not completely cover the cathode, and expands to accommodate more current. Tubes were manufactured for voltages of 75, 90, 105 and 150 that were used like Zener diodes, handling from 5 to 40 mA. There is more information on glow discharges in Relaxation Oscillators, and on Zeners in Voltage Regulators. VR tubes are treated here because of their association with vacuum tubes, and the higher voltages involved.

Experiments

Vacuum tubes generally operate at higher voltages than transistor circuits. Like transistors, vacuum tubes are happier at higher voltages, which for receiving-type tubes, typically would be, say, 200 to 250V. It was once quite common to make DC power supplies for such voltages, using a transformer with a center-tapped secondary (say 200-0-200V), and a rectifier with double anodes and a common cathode, feeding a filter consisting of capacitors of 8 or 16 μF, and a choke of 10 H or so. It was not convenient to make a bridge rectifier with vacuum diodes (three separate filament transformers are necessary), so full-wave rectification with a center-tapped secondary was usual. These days it is rather difficult (and expensive) to acquire all these things, with the possible exception of the capacitors, which are now available up to millifarads at voltages up to 450 V.

The voltages normally used with receiving tubes are not high enough to be really dangerous, though a shock will not improve your day. If you are eager for new experiences, I can save you the trouble of finding out by saying that a DC shock is kind of like a hammer blow, not the zap of an AC shock, and does not paralyze, as an AC shock does. Shocks are given by current, not simple contact, so a good and old rule is to work with one hand in your pocket around high voltage. Always turn things off before making any adjustments or changes, of course, and be neat. Avoid touching bare metal. With these precautions and normal care, you will be fine. The solderless breadboard, DMM and oscilloscope can handle these voltages quite

space charge in the tube increased to the point where its field was capable of offsetting the effect of the field set up by the voltage applied to the plate, and a new and higher value of temperature saturation was attained.

Thus, we see from Fig. 6-9 that for every value of plate voltage there is a limit to the number of electrons which can be drawn over to the plate in unit time to form the plate current. There is consequently a limit to the value of filament or heater current which need be applied. Still another significant detail which appears in the curve, is that if the filament or heater current is not sufficiently great to create space-charge-limited current for any particular value of plate voltage, nothing is gained by increasing the plate voltage. For example, in Fig. 6-9 point X corresponds to 5 units of filament current. All the electrons emitted at this temperature are being attracted over to the plate when the lower value of plate voltage is being applied. Raising the plate voltage to the higher value does not produce any increase in plate current.

Plate Voltage—Plate Current Characteristic

This plate voltage—plate current characteristic curve is far more frequently employed than the one associated with the temperature of the emitter. Here again we find a very peculiar condition as it relates to the diode. Certain very significant theoretical facts can be gleaned from the characteristic curve, but unfortunately it does not have much practical significance because the special conditions created in making these curves are not usually experienced in practice.

Based upon the general discussion of the relationship between the space-charge field in a diode and the field due to the plate voltage, it would seem that a curve which would show the variation in plate current for variations in plate voltage would begin at zero for zero plate voltage. From the previous discussion associated with Fig. 6-8A, we know this not to be the case, for, due to the high-speed electrons which reach the plate without any attracting force being applied to the plate, a small amount of plate current flows with zero plate potential.

Granting that to be the case, it would seem that the plate-current curve would start rising from this small value of plate current for zero voltage, to higher values as the plate voltage was increased until a point is reached where all of the electrons being emitted would find their way to the plate. In other words, the value of plate voltage would then be sufficient to nullify completely the field due to the space charge, so that any further increases in plate voltage for any given value of emitter temperature would cause no further increase in the plate current. This condition is called *plate-voltage saturation.*

A plate voltage—plate current curve would appear like that shown as *ABC* in Fig. 6-10. The electrical system for producing it is shown in the accompanying schematic. E_b indicates the voltage being applied to the plate, and the meter I_b indicates the plate current. Since the emitter temperature is fixed, no meter to measure the filament or heater current is indicated.

Referring to the characteristic curve *ABC*, the point *B* corresponds to the point of plate-voltage saturation, which is reached for a voltage of approximately 300 volts. In contrast to the curve illustrating the relationship between emitter temperature and plate current, that portion of the plate voltage—plate current curve which is rising, represents the zone of space-charge-limiting action upon the plate current. Over all of this portion, as the plate voltage is being increased from zero to about 300 volts, the space charge is also controlling the current. At point *B* the field due to the plate voltage is sufficient to nullify the entire space-charge influence and the plate current becomes limited only by the available emission. From this point on, the plate takes all of the electrons emitted by the cathode.

As you can see from the curve, the point *B*, equivalent to the complete overwhelming of the space-charge control by a plate voltage of about 300 volts, is equal to the flow of about 67 milliamperes of plate current. Increasing the plate voltage beyond this point has been said to be productive of no further increase in plate current. Actually there is a slight increase, for there is always an increase in plate current as the plate voltage is raised. This increase is so small as the plate voltage is raised beyond the upper bend in the characteristic curve, as to justify the statement that beyond point *B*, which is the plate-voltage saturation point, there is no further increase in plate current for an increase in plate voltage.

To secure an increase in plate current for plate voltages in excess of 300 volts, it is necessary to procure a greater flow of electrons per unit time. This means that the temperature of the emitter must be raised. Assuming this to have been done, we can imagine a curve like that shown as *ADE* in Fig. 6-10, Point *D*, corresponding to a plate-current flow of about 85 milliamperes and a plate voltage of about 375 volts, is the point of plate-voltage saturation.

Increasing the emitter temperature has again restored the action of the space charge and it is once more exerting control over the plate

gain in response to increased negative grid bias, which was used for AGC (automatic gain control) in IF amplifiers. The 6SK7 was a very popular remote cutoff pentode used as an RF and IF amplifier. The 6SJ7, on the other hand, was a *sharp-cutoff* pentode, used as an audio voltage amplifier. The amplification factor has little significance with pentodes, as with transistors, and transconductance is the important parameter. The screen grid also acted as an electrostatic shield between control grid and plate, reducing the Miller capacitance to extremely small values, 0.003 pF in the 6SK7. If the screen and suppressor grid are connected to the plate, the pentode operates as a triode.

A very curious and ingenious kind of tube was the *electron-ray* tube, used on receivers to give a visual indication of the accuracy of tuning to a station. Don't confuse it with the *cathode-ray* tube that uses a guided electron beam for oscilloscopes and TV receivers. It showed a luminous disk, with a dark sector. The dark sector was made as small as possible to achieve accurate tuning. It worked from the AGC (automatic gain control) voltage of the receiver. This is a feedback signal that tries to keep the signal amplitude constant at the output of the intermediate frequency amplifiers, increasing the gain for weak signals and decreasing it for strong. It is usually a negative voltage produced by rectifying the IF output. The tube has a thermionic cathode and a conical anode or *target* covered with cathodoluminescent phosphor (like a CRT), which glows from the 3 or 4 mA of plate current that flows when it is across 125V or more (up to 250). Control electrodes, of which there are two on opposite sides of the 6AF6, make two dark sectors that are widest when at 0V, and narrow as the control voltage approaches the target voltage. The control voltage is typically provided by the plate of a triode controlled by the AVC, such that full negative AVC cuts off the triode and makes the sector as small as possible. All this was cheaper and more graphic than a pointer meter.

Another kind of tube that we'll look at here is the glow-tube voltage regulator. The voltage across a glow discharge depends on the gas and the cathode material, and is almost idependent of the current

Although tetrodes worked as expected, they had a serious defect. It happens that speedy electrons colliding with the plate knock out *secondary* electrons. In a triode, these are rapidly sucked back to the positive plate, and the same happened in a tetrode when the plate potential was higher than the screen grid potential. In normal operation however, especially with large voltage gain, the plate voltage has a large swing, and can become less positive than the screen grid. Now all these secondary electrons (and some of the primary ones, too) are attracted to the screen grid, and there is a definite sag in the characteristic in this region. To prevent this, it is necessary to establish an electric field at the plate that is always directed toward the plate, to suppress the escape of secondary electrons. This is provided by a third grid, the *suppressor grid*, which is usually connected to the cathode. The tube with three grids: control, screen and suppressor, or grids 1, 2 and 3, is called a *pentode*, which turns out to be a superior voltage amplifier, fully equivalent to a transistor. A typical small pentode, the 6SJ7, has a plate resistance of over a megohm, and a transconductance of 1.6 mS.

An ingenious modification of the pentode has electrodes that shape and concentrate the electron beam instead of a suppressor grid, the negative space charge of the electrons doing the same work. These are called *beam power* tubes, and were good for power work, as the name indicates. A typical example, the 6L6, had a transconductance as high as 6.0 mS, and the smaller 6V6 about 4.0 mS. Both types were widely used for high-fidelity audio amplifiers, and tube amplifiers still have proponents. The same tubes were used in small amateur radio transmitters, which shows the versatility of vacuum tubes.

Receiving pentodes were also classified as *sharp cutoff* or *remote cutoff*, an example of designing tubes to fit their applications. A remote cutoff pentode had a grid with variable spacing, so that areas of wider spacing let electrons through when the grid was made more negative, when areas of smaller spacing were cut off. This effectively reduced the transconductance of the tube, decreasing its

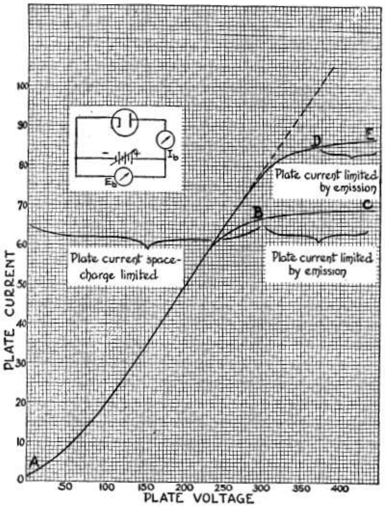


FIG. 6-10. Plate voltage—plate current characteristic. These curves show that the plate current does not increase appreciably above certain values no matter how much the plate voltage is raised, as only a limited number of electrons are emitted.

current against the field due to the plate voltage, until that voltage reached a value of approximately **375** volts. At that point the plate current represented the total number of electrons emitted per unit time by the emitter. Further raising of the plate voltage beyond **375** volts is of little aid in increasing the plate current, because all of the electrons liberated are already traveling to the plate.

From the theoretical viewpoint, the plate voltage—plate current characteristic teaches us that for every diode which is operated at a certain emitter temperature (filament or heater current), there is a certain value of plate voltage beyond which it is useless to increase, for at this value all of the liberated electrons are moving over to the plate.

From the practical angle, however, a different condition occurs. The tube used to develop the plate voltage—plate current characteristic of Fig. 6-10 had a tungsten filament. Were this type of emitter replaced by one with an oxide coating or a thoriated-tungsten type of emitter, it would have been very difficult to find values of plate voltage which would draw off all of the electrons being emitted, that is to reach a point of plate-voltage saturation, without first ruining the tube and thus nullifying all of the work. In other words, modern tubes, most of which have oxide-coated filaments or cathodes, do *not* display a plate-voltage saturation characteristic, but rather show continually rising plate-current curves as the plate voltage is increased, as indicated by the dotted line in Fig. 6-10, until the plate current is so great as to damage the tube.

Under the circumstances, it is needless to elaborate upon the fact that in practice the values of plate voltage applied to two-element tubes are far removed from anything which would even approach the condition of plate-voltage saturation. This, however, plus the condition previously mentioned, does not defeat the value of such a plate voltage—plate current characteristic curve. At least the theoretical data are given and you have become acquainted with the manner in which such curves are used to interpret conditions existing within the tube and the action of the various agencies functioning within the diode. From this point on we shall concern ourselves with the more practical aspects of tubes, and the values of current and voltage which are actually experienced in the daily use of diodes.

Resistance of the Diode

Since the application of a positive voltage to the plate of a diode tube results in the flow of plate current and this current is not infinite but is held within bounds and varies with the plate voltage, it stands to reason that the tube must have some value of resistance. This it does, and the diode, like all other vacuum tubes, possesses two kinds

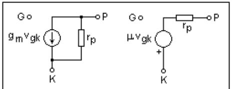
It's easy to see that the maximum voltage gain achievable with a triode is μ, if the load resistance is much higher than the plate resistance. The rule we derived for the gain of a transistor amplifier as the ratio of the collector and emitter resistances holds here as well, expressed by $\mu = g_m r_p$. The quantity analogous to r_e is $1/g_m$, which is 333Ω for the 6J5. Mu is a rather modest number, so triodes are not good for high voltage gain. They make very good power amplifiers, however, since large currents can be controlled. Using the Thévenin source, the gain of a usual common-cathode amplifier (analogous to a common-emitter amplifier) is simply a voltage divider problem. There must be a plate resistor in series with the plate, or else the voltage would never change, but it should be as large as possible, and has only a small effect on the gain. We shall examine these circuits in detail in the experiments, but this provides the background.

In order to provide higher voltage gain, the plate resistance must be reduced somehow. We recall that with a transistor, the analogous collector resistance was very large, and there was no problem with voltage gain. The plate resistance is the result of the effect of plate voltage on the space charge. This effect is not necessary for control, which is provided by the control grid, so what we need is to eliminate the effect of the plate voltage on the space charge. This is done by introducing another grid, the *screen grid* between the control grid and the plate. If this grid is held at a constant potential, the space charge is "screened" from the effects of changes in plate voltage. The screen grid is usually bypassed to ground by a capacitor, whose reactance at the lower corner frequency should be smaller than the resistance connecting the screen grid to B+. Some, but few, electrons are removed by the screen grid, since it is again a coil of fine wire. With this change, the plate characteristics become (nearly) horizontal lines, as for the transistor, and the plate resistance becomes large, approaching a megohm. The resulting tube is called a *screen-grid tetrode*.

voltage electrolytic. Only part of the cathode resistor can be bypassed if some feedback is desired.

A typical triode, of which the 6J5 is chosen here as the example, has a μ = 20, r_p = 6.7k and g_m = 3.0 mS. Of course, the relation $\mu = g_p m_p$ always holds. The value of transconductance may seem small, compared to a transistor, but it should be remembered that it refers to a high-voltage plate circuit, and that the input impedance is infinite, so the power amplification is extremely large. The 6J5 is called a "medium-mu" triode. The similar 6SL7, a "high mu" triode, has μ = 70, r_p = 44k and g_m = 1.6 mS. The 6SL7 is a *dual* triode, two independent valves sharing the same heater. The dual version of the 6J5 is the 6SN7.

The maximum plate voltage of the 6J5 is 300V, and the maximum plate current is 20 mA. Its maximum *plate dissipation* is 2.5W (product of average plate current and average plate voltage). This gives an idea of the ratings of receiving tubes used as voltage amplifiers. As power amplifiers, the allowable plate currents can be quite a bit larger, and hundreds of watts output is possible with relatively small tubes. The interelectrode capacitances of the 6J5 are on the order of 3.4 pF, and are significant at high frequencies.



Triode Equivalent Circuits

The small-signal equivalent circuits for the triode are shown at the right. The Norton source circuit is exactly the one for the FET. In the case of the triode, the plate resistance is always important, and cannot be neglected. The other circuit is just the Thévenin source corresponding to the Norton source. It shows the significance of the amplification factor, and is useful for triodes because of the rather small plate resistance. We did not find the Th%eacute;venin source for transistors very useful, and did not introduce a parameter analagous to the amplification factor for this reason.

of opposition to the flow of current: *d-c plate resistance and a-c plate resistance*. Of these two classifications, the latter is by far the most important.

D-C Plate Resistance of the Diode

As the name indicates, the d-c plate resistance of the diode is that opposition to the flow of current which is offered by the tube when a d-c voltage is applied to the plate. It is that quantity which can be determined by the application of Ohm's law for resistance, employing the applied d-c plate voltage and the measured value of d-c plate current as the known quantities in the equation.

For example, Fig. 6-11 illustrates a typical plate voltage—plate current characteristic for a typical 6H6 duo-diode tube, using just one pair of elements. By one pair of elements is meant one cathode and its associated plate. The plate voltage applied to the tube is shown upon the horizontal axis of the graph and the resultant plate current is shown upon the vertical axis. While this is the same as is found in the plate voltage—plate current characteristic curve illustrated in Fig. 6-10, the general shape of the two characteristic curves is quite different. This comes about as the result of the special conditions mentioned in connection with Fig. 6-10. The curve shown in Fig. 6-11 is a closer approach to the actual curve with which you will work.

You will remember that we qualified the conditions indicated in the curve of Fig. 6-10 to the extent that the plate-voltage saturation points were not to be expected when using oxide-coated filament or cathode type tubes. The 6H6 is an oxide-coated tube and it is evident in Fig. 6-11 that plate-voltage saturation is a long way off. In fact, judging by the values of plate current which prevail for the comparatively low values of plate voltage, it is doubtful if the plate-voltage saturation point could ever be reached. More than likely the tube would be damaged long before that value could be reached by the application of sufficient plate voltage.

With a comparatively low value of plate voltage, say 28 volts, applied to the plate, the formidable value of about 66.4 milliamperes of current already flows in the tube. And judging by the slope of the plate-current curve, the steep portion is yet to come, that is, if we increased the plate voltage above 32 volts. There is little doubt that were this plate voltage increased to say 50 or 60 volts, the plate current would rise to such a value as to destroy the tube. This does not mean that diodes are not used at plate-voltage values greater than 32 volts. Much higher values of plate voltage are employed, but when

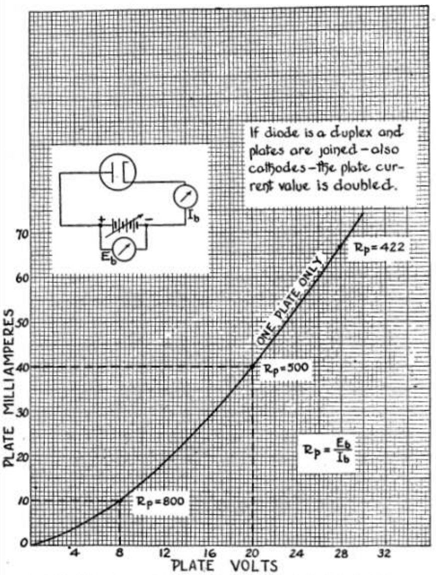


FIG. 6-11. Plate voltage—plate current characteristic for a typical 6H6 diode tube.

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A vacuum tube carrying a current I with a plate voltage V dissipates power VI, just as if it were a resistor. However, the process is different. In a resistor, an electron gives up small amounts of energy to the lattice as it is accelerated and then is scattered. In a vacuum tube, the electron acquires a kinetic energy as it is accelerated, which it gives up all at once when it collides with the plate. It is not really correct to ascribe this to the "plate resistance," as some texts do, which is an incremental ratio. Since the plate is in a vacuum, the resulting heat can only be radiated or conducted down the supports. Much of the radiated heat is infrared, which is absorbed by the glass tube envelope. Note how plates are blackened to raise their emissivity and often provided with fins. Really large tubes had plates externally exposed capable of air or water cooling with elaborate seals to the glass parts. *Plate dissipation* is always a limiting factor in power applications.

The line marked *load line* shows the difference between the supply voltage V_{bb} and the voltage drop in a resistance R_L in series with the tube at any plate current, giving the plate voltage directly. The series resistance is mainly a plate resistor, but if there is a cathode resistor (for purposes of biasing) it should be included. There are generally different load lines for static (DC) and dynamic (AC) operation. As the grid voltage is varied, the plate current and voltage vary along the load line. The quiescent or operating point can be selected at some point along the DC load line, and so the DC grid bias can be found. This grid bias can be obtained from a C battery or equivalent, or from a cathode resistor, just as an emitter resistor is used with a transistor.

A cathode bias resistor is often bypassed by a capacitor if its negative feedback effect is not desired in dynamic operation. The reactance of the capacitor at the lower corner frequency should be equal to the resistance looking into the cathode (normally $1/g_m$ in parallel with the cathode resistor). The size of the cathode resistor has only a small effect on the size of the bypass capacitor. The capacitor never has a large voltage across it, and can be a low-types can have quite different (though similar) characteristics, so characteristic curves are much more important.

Let's begin with idealized plate characteristics for a triode, shown at the right. These are curved lines, but we represent them by straight lines for ease of understanding the various slopes and distances involved, which will be constant. Actual characteristics are not really far from straight lines, anyway. There is one curve for each grid voltage represented, which differ by a constant amount, here 2V. The horizontal distance between them, represented by the line labelled μ, is the amount the plate voltage must increase to hold the plate current constant; it represents the relative influence of plate and grid on plate current, and is the *amplification factor*. The vertical distance between them shows how much the plate current changes for a change in grid voltage. The ratio is a conductance, called the *transconductance,* denoted by g_m, measured in siemens (mho). The slope of the curves is the ratio g_m/μ, called the *plate conductance* g_p. With vacuum tubes, the reciprocal r_p was always used, called the *plate resistance*. Since actual characteristics are curved, these quantities vary for different currents and voltages.

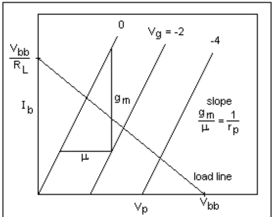


Plate Characteristics

What we desire to represent is a function of two independent variables $I_p(V_p,V_g)$, which can be represented as a surface in three dimensions. Our various characteristic curves are orthogonal views along one or another of the axes. There are three such views possible, each directly related to one of the three parameters, of which we generally use only two, the ones mentioned here.

that is done other elements which tend to keep the plate current to a safe value are also used in the circuit. Such additions will be discussed later.

As we discussed earlier in this text, the plate-current curve of a diode, like that of other vacuum tubes, is of great importance. In this particular instance it serves to furnish information relative to the opposition offered by the tube to the flow of plate current; in other words, it furnishes information about the d-c resistance of the tube. For example, with **8** volts d-c E_b applied to the plate, the plate current I_b, as shown upon the vertical axis, is **10** milliamperes or **0.01** ampere. According to the Ohm's law, these values of plate voltage and plate current represent a d-c plate resistance of

$$R_p = \frac{E_b}{I_b} = \frac{8}{.01} = 800 \text{ ohms}$$

With **20** volts d-c applied to the plate of the tube, we note from the curve that the plate current is **40** milliamperes or **0.04** ampere. This corresponds to a d-c resistance equal to **20/.04 = 500** ohms. With **28** volts d-c applied to the plate, the plate current according to the curve is **66.4** milliamperes or **0.064** ampere and the equivalent d-c resistance is **28/.0664 = 422** ohms.

Examining these three values of d-c plate resistance for three values of applied d-c plate voltage, we note a peculiar condition. The opposition which *the diode offers to the flow of the plate current is not constant*, as we are ordinarily accustomed to experiencing in conventional d-c systems. Said differently, *the resistance offered by the diode to the flow of the plate current is not linear.* Judging by the relationship between the plate voltage, plate current, and the equivalent d-c resistance, it appears that the resistance of the diode *decreases* as the plate voltage is increased, and *increases* as the plate voltage is decreased. Were the resistance of the diode linear over the entire range of plate voltage, the plate-current curve would be a straight line instead of the curved line appearing in Fig. 6-11. Such a straight line would indicate that the d-c plate resistance remained constant over whatever range of plate voltage and plate current is embraced by the upper and lower limits of the straight line.

Of further interest in connection with the plate voltage—plate current characteristic given in Fig. 6-11, is the condition created when the two plates of this duo-diode tube are joined in parallel and the two cathodes are connected in parallel. The plate current for such parallel connection is equal to twice the amount that would occur if the same value of plate voltage were applied to a single pair of elements. Thus, if the plate current for the single diode is 10 milliamperes with 8 volts d-c applied to the plate, the parallel connection of the two plates and the two cathodes results in 20 milliamperes of current, and a d-c resistance of 400 ohms. In the same way, the values of plate current corresponding to any point along the plate current curve of Fig. 6-11 for any value of plate voltage, are doubled when both sections of the duo-diode are connected in parallel and the plate resistance is half of that existing when just one pair of the two diode sections is employed.

You may wonder why the plate current corresponding to zero plate voltage is zero in Fig. 6-11, whereas in Figs. 6-8(A) and 6-10 we mentioned the flow of a small amount of current. There is no conflict between these two conditions. Inasmuch as the value of plate current is so very low when the plate is zero, we felt that no misunderstanding would result by showing the plate current at zero, since it would in no way interfere with the interpretation of the facts shown in the graph.

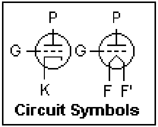
A-C Plate Resistance of the Diode

When we first mentioned the opposition which the diode tube offered to the flow of plate current we said that two types of resistance existed. The d-c plate resistance has been discussed; now we shall look into the a-c plate resistance. Referring again to the basic function of the diode as a converter of a-c electrical power into d-c electrical power, it would appear reasonable if we said that in most instances the voltage which is applied to the diode tube plate is of alternating character rather than the d-c voltage which we discussed in connection with Fig. 6-11. Hence it is logical that any quantity which is associated with the manner in which the tube is used, is more important than some other which is only infrequently involved in the various technical considerations of the tube. The a-c plate resistance is, as a rule, the only term associated with the resistance of the diode when the term "resistance" is employed without qualification. The same is true also for other types of vacuum tubes; that is, when the term "resistance" is employed, it practically always refers to the a-c resistance.

Before we start discussing the a-c plate resistance of the diode tube, we might as well say a few words about a matter of notation which is used in connection with such a-c quantities. When investigating the action of alternating potentials or currents in vacuum tubes, the simplest means of simulating the application of an alternating potential is to vary a d-c voltage about a fixed value. The maximum variations in

was arbitrary. Filaments were customarily used, especially in power and rectifier tubes, because they gave more current per watt of heating power. The indirectly heated, equipotential cathode that could be supplied by AC rather than by battery power was widely used after 1930.

A tube with just cathode and anode is called a *diode*, a term that has survived into the semiconductor age. Diodes were used for power or signal rectification, just like their semiconductor relatives. A "full-wave" diode has two anodes. When a control grid is provided, the tube is called a *triode*, and is used for amplification. Let's first study the peculiar circuit behavior of triodes, which will lead us to the reason for the addition of more grids, and the creation of the *pentode*, which turns out to act very much like a transistor.



Circuit symbols for a triode are shown at the right, and other tube symbols are derived from it. The connections are plate P, grid G, and cathode K or filament F, F'. These are analogous to the collector, base and emitter of a transistor, with the same polarities and direction of current flow as an NPN transistor. The circle is a part of the symbol. Grid connections can be to the right or left of the symbol, as convenient. A gas tube is indicated by a dot in the lower right-hand part of the circle. The heater of an indirectly heated cathode is usually not shown. A cold cathode (operating by positive-ion bombardment) is shown as a small circle. There are examples of these symbols below.

The important variables are the independent variables V_p and V_g, the plate and grid voltages (with respect to the cathode), and the dependent variable I_p, the plate current. A plot of I_p against V_p for a fixed value of V_g is called a *plate characteristic*, and a plot of I_b against V_g for a fixed value of V_p is called a *transfer characteristic*. From a family of either characteristics, the complete circuit behavior of the tube can be predicted. Unlike transistors, tubes of different usually). Inside is a tungsten heater wire insulated from the cathode with BeO or alundum (aluminum oxide) ceramic insulation. These cathodes must be heated only to about 850K (a dull red) to emit electrons in the amount necessary. Most receiving tubes require 6.3V or 12.6V for their heaters, at about 0.30A or 0.15A, respectively. Every tube type is identified by a type number, such as 6J5, where the first number indicates the heater voltage. 6 means 6.3V, 12 means 12.6V. Heaters are very forgiving of variations in voltage, but it is best to try to use the recommended voltages. AC is generally used, supplied from a small transformer. It is necessary to make sure that the difference in voltage between heater and cathode does not exceed 90V, so the heater AC supply should be grounded. It is usual to ground the center tap on the transformer for this purpose. Tubes for battery radios have plain filaments that are both heater and emitter, and must be supplied with DC. Their type numbers begin with "1" and are intended to be used with a standard dry cell of 1.5V. Larger tubes for high voltages have to use thoriated-tungsten filaments at 2000K,a bright yellow, to avoid damage from positive-ion bombardment, small as it may be. Heaters are sometimes called filaments, and the heater supply the filament supply, out of linguistic inertia.

Before the 1930's, each manufacturer used arbitrary designations for his tubes, and there was no uniformity or system. Tubes were first systematically identified in the U.S. by three-digit numbers, where the first digit denoted the manufacturer. For example, a type x10 was a power triode, a type x36 a screen-grid tetrode, where x was the manufacturer's number (usually omitted). Later, a new system was introduced where the first digit gave the filament or heater voltage, and the last digit gave the number of functional electrodes. This scheme was introduced by the RMA (Radio Manufacturer's Association) in 1934. A letter between these digits was assigned in order of introduction. For example, a 2A3 was a power triode with a 2.5 V filament (this popular tube is, remarkably, still in use for hi-fi amplifiers because of its low distortion!). This system was not comprehensive enough, and in the final system, the first number designated the heater voltage, but the remainder of the designation

voltage on both sides of some average value, would represent the peak a-c voltages. The magnitude of these variations is, of course, a matter of individual preference in any experimental work; as a rule it is kept quite low.

When referring to such small changes in applied voltage it is customary to denote the change by the small letter "d," which signifies a "small change of." Thus if we are speaking about a small change in voltage E, we may write "dE" to symbolize the entire expression "a small change in the voltage." Similarly, if I represents current, the symbol "dI" would signify "a small change in current." We can of course extend the idea to whatever quantities are desired. Thus if we wish to represent the resistance represented by "a small change in voltage" divided by "a small change in current," the expression would appear as

$$r = \frac{dE}{dI}$$

Because of what is done in ordinary algebraic calculations where a similar letter appears in both the numerator and the denominator, that is, the cancellation of the same letter from both the numerator and the denominator, as for example

$$\frac{3a}{4a} \text{ can be rewritten as } \frac{3}{4}$$

we have to mention that such cannot be done with the letter "d" for it is not an algebraic unknown in the usual sense, but rather as we have pointed out, signifies an operation which is expressed by the phrase, "a small change of."

In accordance with the above, we show a typical plate voltage—plate current characteristic curve in Fig. 6-12 for one section of the 6H6 diode, which, as you can see, is exactly the same curve as was used in Fig. 6-11. To establish the a-c resistance at any point along this curve, we vary the plate voltage on both sides of some definite value. Thus we know from Fig. 6-11 that the d-c plate resistance of this diode is 500 ohms when the plate voltage is held constant at 20 volts d-c. What is the a-c resistance when the mean value of this assumed a-c voltage is 20 volts and the swing in voltage is 1.6 volts on each side of the mean of 20 volts? In other words what is the a-c plate resistance when de_p is equal to 3.2 volts?

To get the answer we check the plate current for a d-c plate voltage of 21.6 volts and find that it is 45 milliamperes or .045 ampere. Then the plate voltage is reduced to 18.4 volts and we find that the plate

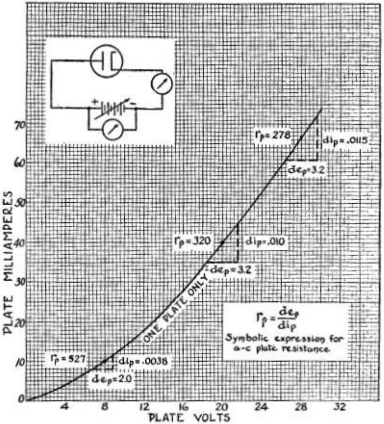


FIG. 6-12. The a-c plate resistance of a diode can be determined from the plate voltage—plate current characteristic as explained in the accompanying text.

current is 35 milliamperes or .035 ampere. We now have the two limits of voltage and the two limits of current. Then the symbol "de_p" represents the *change in plate voltage* or the difference between 21.6 and 18.4 or 3.2 volts. And the symbol "di_p" represents the corresponding *change in plate current* or the difference between .045 and .035 or .010 ampere. The a-c plate resistance r_p then can be expressed as

$$r_p = \frac{de_p}{di_p} = \frac{21.6 - 18.4}{0.045 - 0.035} = \frac{3.2}{0.010} = 320 \text{ ohms}$$

This value of 320 ohms is the a-c plate resistance for a value of plate voltage which fluctuates between 18.4 and 21.6 volts, whereas

can take over a large part of the electron emission at the cathode. Such tubes make efficient rectifiers, and the gas pressure can be quite low, as in some rectifiers, or rather high, as in a mercury-arc rectifier. In receiving tubes, positive ion collisions can destroy the delicate, high-efficiency cathode surface. Positive ions also cause small currents to negative electrodes that otherwise might be expected to carry no current at all. For all these reasons, receiving tubes have a high vacuum.

The electric field at the space charge that controls the current does not have to be created by the anode alone. A third electrode, the *grid*, is placed between the cathode and the anode, closer to the cathode. It is made of a spiral of fine wire, so electrons can pass through without hindrance. When it is made negative, it opposes the effect of the anode in creating an electric field, but does not attract any electrons, and so draws no current (except for the positive-ion current mentioned above). If it is made sufficiently negative, it can *cut off* the plate current entirely. If it is made positive, it can enhance the plate current, but then draws some *grid current* itself. The grid provides a sensitive control, using negligible power, of the large plate current, so the vacuum tube is a powerful amplifying device.

Early radio sets were battery-powered (domestic electrification was in its infancy, and absent in rural areas, when radio began), and a convention was established for identifying the batteries required. The filaments required low voltages at high currents (2W or more each), and their supply was called the A battery. The plates required high voltages at small currents, perhaps 90V at a few mA, and their supply was called the B battery. Grid bias was required, to hold the grids negative, demanding low voltages at small currents, and the corresponding battery was the C battery. The notations A and C were later little-used (except for actual battery radios), but the plate supppy came to be generally known as B+, and the letter B appears in subscripts of quantities referring to the plate circuit.

The cathodes of receiving tubes consist of a sleeve of nickel alloy coated with a compound of alkaline-earth oxides (Ba and Sr, did these cathodes have a long life, but were also *equipotential*, making circuit design simpler. Thoriated tungsten remained for transmitting tubes, where a rugged emitter was necessary because of the higher plate voltages, but even here tungsten was the only suitable choice for really high voltages, to avoid damage from positive-ion bombardment.

The rate of emission of electrons from a heated metal is given by the Richardson-Dushman equation, $i = AT^2e^{-b/T}$ A/cm^2, where T is the absolute temperature in K, and A and b are constants typical of the emitter. For tungsten, A = 60 and b = 52,400K, while average values for an oxide cathode are A=0.01, b = 11,600. The exponential factor has by far the largest influence, so emission increases rapidly with temperature. This makes thermionic cathodes very suitable even for heavy currents. In all tubes, electrons are emitted in far greater numbers than required; most simply return to the cathode.

The electrons emitted by the thermionic cathode form a negative *space charge* cloud around the cathode, dense enough that if no electrons are removed by attraction to the anode, the rate of emission is equal to the rate of return. When the anode is made positive, some of the electrons are attracted to it out of the space-charge cloud, and a *thermionic current* results. The amount of this current is given by $I = A\ V^{3/2}$, where V is the voltage from anode to cathode. This is called the Langmuir-Child law, and shows that electric field at the space charge produced by the anode controls the electron current. The cathode emits electrons copiously, so much that there are always enough electrons available to satisfy Langmuir-Child. Of course, at a sufficiently high anode voltage, the current may *saturate*, when all the emitted electrons are attracted to the anode, but this never occurs in normal operation, so small variations in cathode temperature have no effect. The current in a vacuum tube is said to be *space-charge controlled*.

If enough gas is present in the tube, the positive ions can counterbalance the negative electron space charge, robbing the anode of control and greatly increasing the current. Also, the positive ions

the same point is equal to a d-c plate resistance of 500 ohms when the plate voltage is held constant at 20 volts.

Employing the same method we secure a value of 278 ohms a-c plate resistance at the 28 volts plate-voltage point for a change in plate voltage of 1.6 volts each side of the mean value of 28 volts. This compares with a d-c resistance of 422 ohms when the plate voltage is maintained constant at 28 volts.

You may have noted the difference in symbols used to denote d-c and a-c plate resistance. The former is shown with a capital "*R*" and a small sub-letter "*p*", whereas the a-c plate resistance is designated by a small "*r*" and the sub-letter "*p*". This is commonplace in vacuum-tube literature. In fact capital letters are usually used to identify *d-c fixed quantities*, whereas small letters indicate *varying* or *a-c quantities*. (See page 407.)

Thus we find that the d-c plate resistance and the a-c plate resistance differ appreciably. *The same is true for all types of vacuum tubes*, not only diodes, and this is well to bear in mind. As a rough approximation, the a-c plate resistance is equal to about one-half of the d-c plate resistance. Furthermore, as you can see from the illustrations given in Fig. 6-12, the a-c resistance is also related to the plate voltage, decreasing as the plate voltage is increased, and increasing as the plate voltage is decreased. The exact value of a-c resistance depends upon the point of operation selected on the plate-current curve. Thus, if the point of operation is at a plate voltage of 20 volts, the a-c plate resistance is greater than when the operating point chosen corresponds to a mean plate voltage of 28 volts.

Static and Dynamic Diode Characteristics

The various schematic diagrams of diode systems given in this chapter were typical of circuits employed in the development of the plate voltage—plate current characteristic curves and those required for a simple discussion of the plate current. They did not, however, represent circuits as used in practice. In order that a diode be capable of performing its normal function as a converter of electrical power of a-c character into power of d-c character, its external circuit must contain a *load*. It is through this load that the diode tube current flows outside of the tube, and the voltage drop developed across this load is then representative of the so-called "output" of the tube.

When such a load resistor is added to a diode circuit, as R_b in Fig. 6-13, the operating characteristic of the tube undergoes a major change, that is, the shape of the plate voltage—plate current curve is materially altered. It now becomes the *dynamic* characteristic rather than the *static* characteristic which exists when there is no load.

The reason for this change in characteristic is simple to understand. When there is no load in the circuit or $R_b = 0$, the current in the tube circuit is determined entirely by the resistance of the tube itself. If an external resistance, which we identify as the *load resistance*, is added to the circuit, as in Fig. 6-13, the total opposition to the flow

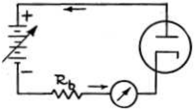


Fig. 6-13. The load resistance, R_b, and the tube resistance are in series and they form the total opposition to the flow of the plate current. The internal resistance of the battery is neglected.

of current is no longer the resistance presented by the tube itself, for it now includes the load resistance as well as the plate resistance. If we select a value for this load resistance which is many times the internal resistance of the tube, the effect of the tube resistance upon the amount of plate current flowing in the entire system is made negligible. Accordingly, if the external load resistance is of such a character that it maintains its resistance regardless of the amount of current flowing through it, that is, irrespective of the voltage applied across its terminals, the plate voltage—plate current characteristic of the system is changed from a curved line to a substantially straight line.

We may show these various conditions upon a separate graph, as illustrated in Fig. 6-14. The dashed line represents the static characteristic of plate voltage and plate current, that is, when the load resistance is zero. Solid line (1) indicates the voltage—current relationship when the load resistance is 1,000 ohms. This line still has a considerable curvature, but much less than that possessed by the static line. When the load resistance is 10,000 ohms, we obtain solid line (2). This line is fairly straight, its main curvature appearing at the region of low plate voltage where the internal resistance of the tube is the highest. The line representative of the 100,000-ohm load resistance is so straight throughout its entire length and lies so close to the horizontal axis that it would have been impractical to draw it.

Concerning the straightening of the plate voltage—plate current characteristic of the diode by the addition of the load so as to produce the required linear dynamic characteristic, the higher the value of load

positive ions, which can cause emission of electrons or even heat the cathode the required amount for thermionic emission. All receiving tubes employ thermionic emission, though we will note certain examples of *cold cathodes* in special cases. These were not usually really cold, but heated by ion bombardment rather than by a current supplied externally. The space in which the electrons move is not completely devoid of gas, so some gas molecules may be *ionized* by collision with speedy electrons, when an electron is knocked off, leaving a *positive ion*. The positive ions move in the opposite direction to the electrons (but their current is in the same direction, since they are of opposite charge). The effect of positive ions in a receiving tube is very small, because of the very high vacuum that is used.

Self-heated electron emitters are called *filaments*. The carbon filaments of the Edison Effect were soon replaced by metallic emitters, usually tantalum or tungsten, which were used by Fleming and de Forest. In Germany, Arthur Wehnelt discovered in 1903 that barium or calcium oxides baked on a platinum base emitted copiously, and used these *oxide-coated* emitters on vacuum rectifiers evolved from discharge tubes, which he patented in 1904. However, the use of *soft* tubes, which contained residual gas, demanded the use of rugged tungsten filaments, which dominated in 1910-20. These filaments used low voltages and high currents, and had a short life because of the high temperatures required for adequate emission. Most radio sets had a rheostat to adjust the filament current properly. Wehnelt emitters would have been quickly destroyed by positive-ion bombardment in these tubes. Apparently by accident, thoriated tungsten wire was used in a trial at the GE factory in Harrison, NJ in 1920 on a UV201 tube. Thoriated tungsten gave 75 mA/W of filament power, while tungsten gave only 1.75. Thoriated-tungsten filaments became popular for receiving tubes, such as the UV201A, which was an improved UV201, around 1924. Its filament required 0.25 A at 5 V, while the UV201's had required 1.0 A. Since tubes were now all *hard*, or high-vacuum tubes, indirectly heated oxide-coated cathodes, which gave copious emission at low temperatures, were used almost exclusively in receiving tubes after 1930. Not only "triode" was not used until much later, after it threated to become a trade name), in which a third electrode, the grid, was introduced to control the electron stream. This made a more sensitive detector, but the amplifying property was not used at first, and de Forest, who did not understand well what was going on, defended gassy tubes with their gas amplification. The introduction of high vacuum, as well as improved materials and processes, especially metal-to-glass seals, created a very useful amplifying device that allowed great developments in radio, telephony and sound reproduction. Schottky suggested a screen grid between the plate and control grid to make the electron tube useful at higher frequencies in 1919 (and actually made tubes with a second grid, but this was for space-charge control), but this was only realized by Hull and Williams in 1928 in radio receivers. The metal tube was introduced in 1935, but glass envelopes never disappeared and were constantly improved. The final pattern of electron tube was the "miniature" or all-glass type, which became the predominant receiving-type tube after about 1945. Transistors were invented in 1948, and in the next decade were improved to the point where they could take over most of the amplifying applications of electron tubes at much lower cost, and with greater reliability. Electron tubes remain in use as cathode-ray tubes, magnetrons, X-ray tubes, and for handling large powers. They were remarkable devices, using many sophisticated materials and processes, yet were widely available at low cost. We shall look here mainly at examples of *receiving tubes*, the smaller amplifying devices that have been completely replaced by semiconductors in current practice, but nevertheless will deepen our knowledge of electronics, while being fascinating to study. The name "receiving" comes from their use in radio receivers, their principal commercial application, but refers to all small vacuum tubes for general electronic purposes. For the cathode-ray tube and making your own oscilloscope, see [The Cathode-Ray Tube](#).

The electrons move from the cathode (K), the negative electrode, to the anode or *plate* (P), the positive electrode. Conventional current is in the opposite direction. The electrons are liberated at the cathode by heat--thermionic emission--or as a result of bombardment by

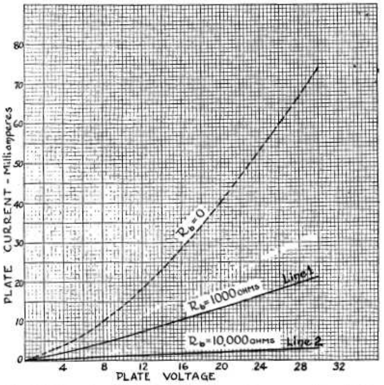


FIG. 6-14. Lines 1 and 2 are the plate voltage—plate current characteristics of a diode having a load resistance of 1000 and 10,000 ohms respectively.

resistance, the straighter is this dynamic curve. At the same time, however, the lower is the amount of plate current which flows in the circuit. This is not harmful, provided that the value of the load resistance is kept within reasonable limits.

Having read all of this information about the difference between the static and the dynamic plate voltage—plate current characteristics, and the effort to make this curve straight, you may wonder why this is done. The primary reason is that when the diode characteristic is straight, its action in certain portions of radio communication systems is substantially free from the production of distortion and this is greatly to be desired. There are, however, various applications of the diode, in which the exact nature of this characteristic is not of particular significance, although it should be understood that some straightening action takes place concurrently with the use of a load, and some sort of a load is required in order to make the diode of practical value.

It is also of importance to realize that the higher the load resistance used in a diode circuit, the greater is the permissible voltage which may be applied to the plate without fear of causing the flow of such high values of current that will damage the tube. You can see from the plate current values shown in Figs. 6-11 and 6-12 that the application of several hundred volts to the plate will cause the flow of such very high values of plate current as to damage the tube, unless high values of load resistance are used, which reduce the plate current to permissible values.

A-C Applied to the Diode Plate

It is necessary to speak briefly about the application of an alternating voltage to the plate of the diode. The reason is that everything we have said so far has shown d-c voltage applied to the plate, although we mentioned that the basic function of the diode was as a converter of a-c power into d-c power. The characteristics we have mentioned and developed by means of d-c voltages upon the plate are those which exist when a-c voltages are applied to the plate, for, in

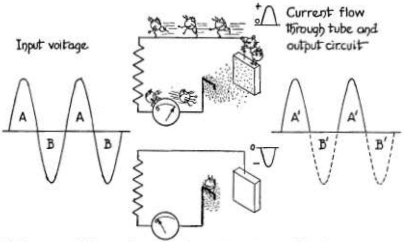


Plate current flows during positive alternation and plate is positive with respect to cathode. Plate current does not flow when plate is negative with respect to the cathode. Thus output current and voltage is unidirectional although input is alternating.

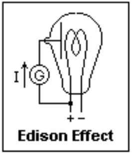
Theory of Vacuum Tubes

J. B. Calvert

Created 17 August 2001
Last revised 8 April 2003

http://mysite.du.edu/~etuttle/electron/elect27.htm#Diodes

Miniature vacuum tubes with cathodes of high-field-emitting carbon nanotubes are currently under study at Agere Systems in Murray Hill, NJ. A triode with amplification factor of 4 has been constructed, with an anode-cathode spacing of 220 μm, and a pentode is planned. Vacuum tubes may return to electronic technology! See *Physics Today*, July 2002, pp. 16-18.



Devices in which a stream of electrons is controlled by electric and magnetic fields have many applications in electronics. Because a vacuum must be provided in the form of an evacuated enclosure in which the electrons can move without collisions with gas molecules, these devices were called *vacuum tubes* or *electron tubes* in the US, and *thermionic valves* in Britain. In 1883, Thomas Edison observed that a current flowed between the filament of an incandescent lamp and a plate in the vacuum near it (see figure at the right), when the plate was connected to the positive end of the filament, but not when the plate was connected to the negative side (the plate was actually between the two legs of the filament). No important application was made of this unexplained *Edison Effect* at the time. In 1899, J. J. Thomson showed that the current was due to a stream of negatively-charged particles, electrons, that could be guided by electric and magnetic fields. Fleming patented the *diode* in 1904 (B.P. 24850), where a filament and plate were arranged in the same envelope in a rather low vacuum, which could be used as a rectifier, or as a rather insensitive radio detector. In 1907, Lee de Forest patented the *triode* (which he called the Audion; the term *d.* A linear dynamic characteristic is desired for the diode, principally because it assures proportionality between applied plate voltage and output current. This affords freedom from distortion in many circuits that use the diode, although, in other applications, distortion is of secondary importance. The most important consideration is the use of a load; a *load* is necessary if a diode is to be of practical use.

27. Uses

a. Since current flow in the diode is unidirectional, one of its most prominent uses is as a rectifier or converter of alternating current into direct current. In figure 36, an alternating voltage is used as the plate voltage. During the positive alternations of the input voltage, the plate is positive relative to the cathode, and plate current i_p flows through the tube and load resistance R_L. The current develops a voltage drop across the load. At every instant the output voltage (in volts) is:

$$e \text{ output} = (i_p \times R_L) - (i_p \times r_p)$$

where R_L is the load resistance in ohms

r_p is the a-c resistance of the diode in ohms

i_p is the instantaneous current in amperes.

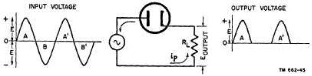


Figure 36. Diagram illustrating unidirectional current flow in diode.

b. If load resistance R_L is very much greater than r_p, the internal tube resistance, the effect of the latter is negligible and i_p times r_p of the preceding formula can be neglected.

c. Concerning the action in figure 36, it can be seen that the changes in current amplitude follow the instantaneous changes in applied plate voltage. This becomes evident when the input plate-voltage alternations, A and A′, are compared with the output voltage pulsations, A and A′. These pulsations have the same shape as the two positive alternations of the applied voltage. The absence of conduction in the tube during the two negative alternations, B and B′, of the input voltage is caused by the diode plate being negative with relation to the cathode during these periods. If the input voltage has a frequency of 60 cps (cycles per second), the output current pulses will occur 60 times per second, each lasting for a period equal to one-half of each input cycle.

d. Both single- and dual-section diodes have many other uses, developed later in this manual. All of these depend on the principle of unilateral conduction through the tube.

28. Types

High-vacuum diode tubes are available in various types (fig. 37), differing principally in physical dimensions and shape. They differ internally as well but not in the fundamental arrangement of the electrodes. The physical dimensions are related to the magnitudes of voltages applied to the plate and the currents flowing through the tube during operation. Tubes used in circuits which handle signal voltages of relatively low values are known as signal diodes. Another general category is that of power diodes or vacuum-tube rectifiers which handle high values of voltage and current. Each of these types is intended for special application and they are not interchangeable. Signal diodes are restricted to signal circuits. Power diodes generally are used in power circuits, except where certain signal systems entail relatively high voltages, and circuit operation demands an action similar to rectification.

29. Electron Transit Time

a. The time required for an electron to traverse the distance from the cathode to the plate of a diode, or other kinds of electron tubes, is

the final analysis, the tube operates only on one half of the a-c voltage wave, that is, during that time when the plate is positive with respect to the cathode. Therefore, the conditions which exist in the tube during that positive half cycle can be simulated by the application of d-c voltages.

b. With no load in the circuit, or when R_L equals 0, the resistance in the circuit is the resistance of the tube; also, the small resistances of the battery and meter are present, but these can be neglected. But when an external resistance, the *load resistance*, is added (fig. 34), the total opposition to plate-current flow includes that of the tube itself and also that of the load. When the load resistance is many times the value of the internal resistance of the tube, the tube resistance offers only a negligible percentage of the opposition to plate-current flow. Consequently, if the external load resistance maintains its value regardless of the amount of current flowing through it, the plate-current plate-voltage characteristic of the system is changed from a curved line into a substantially straight line.

c. These various conditions can be noted on a separate graph (fig. 35). The dashed line represents the static characteristic—that is, when there is no load resistance. Solid line 1 illustrates the voltage-current relationship when the load resistance is 1,000 ohms. This line possesses some curvature, but it is considerably less than that of the static line. Solid line 2 is obtained with a load resistance of 10,000 ohms. This line is almost straight; some curvature appears in the region of low plate voltage where the internal resistance of the tube is highest. A line representing a value of 100,000 ohms is so straight throughout its length that it lies too close to the horizontal axis, and it cannot be drawn clearly on the graph. Therefore, the higher the load resistor value, the straighter is the dynamic curve, and the lower is the amount of plate current flowing in the circuit. This is not a disadvantage, provided the load resistance is maintained within reasonable limits.

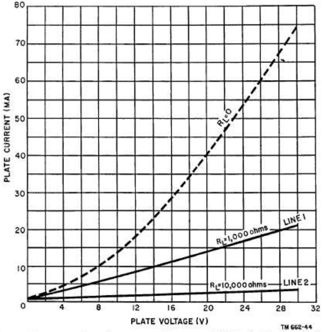


Figure 35. Plate-current plate-voltage characteristic curves of diode having different load values.

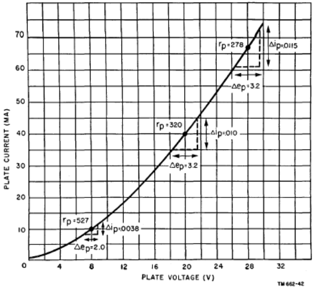


Figure 33. Plate-current plate-voltage characteristic which can be used to determine the a-c plate resistance of a diode.

lected on the characteristic curve. Consequently, if the point of operation is at a plate voltage of 20 volts, the a-c plate resistance is greater than when the operating point chosen corresponds to a mean plate voltage of 28 volts.

26. Static and Dynamic Diode Characteristics

a. The discussion of diodes thus far has been for static conditions and not for actual operating conditions. For a diode, or any tube, to be able to perform its normal function, its external circuit must contain a *load*. It is through this load that the diode current flows outside the tube, and the *voltage drop developed across this load then represents the output of the tube.* With such a load, represented by a resistance R_L (fig. 34), the operating characteristic of the tube is changed materially. The plate-current plate-voltage curve is altered noticeably, and it represents the *dynamic* characteristic rather than the *static* characteristic which applies when there is no load.

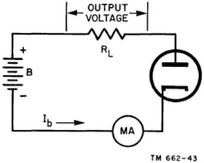


Figure 34. Adding a load resistor, R_L, to a diode circuit to obtain an output voltage.

PRINCIPLES
OF
ELECTRON TUBES

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First Edition

McGRAW-HILL BOOK COMPANY, Inc.
NEW YORK AND LONDON
1941

CHAPTER 2

THERMIONIC EMISSION; THE HIGH-VACUUM THERMIONIC DIODE

The operation of the majority of electron tubes is dependent upon thermionic emission. The theory of thermionic emission is therefore of great importance in the study of electron tubes. It is the purpose of this chapter to discuss the basic principles of thermionic emission, the construction of practical emitters, and the flow of electron space current in high-vacuum tubes containing two electrodes.

2-1. Theory of Thermionic Emission.—Richardson's theory of the emission of electrons from hot bodies is in many respects analogous to the kinetic theory of vaporization.[1] Heat possessed by a metal is believed to be stored not only in the kinetic energy of random motion of atoms and molecules, but also in the kinetic energy of free electrons. As a result of collisions between electrons or between electrons and atoms or molecules, the speed and direction of motion of a given electron are constantly changing. At any instant there will be, close to the surface of the metal, some electrons that have a component of velocity toward the surface of such magnitude that the corresponding kinetic energy is equal to or exceeds the electron affinity. If these electrons reach the surface without colliding with atoms, they will pass through the surface. At room temperatures the number of electrons meeting this requirement is extremely small, and hence no thermionic emission is detectable. As the temperature of the emitter is increased, however, the average velocity of the free electrons increases. The number having velocity components toward the surface sufficient to allow them to escape, therefore, increases with temperature. Reduction of electron affinity reduces the velocity toward the surface necessary to allow an electron to escape, and so increases the number

[1] RICHARDSON, O. W., *Proc. Cambridge Phil. Soc.*, **11**, 286 (1901); "Emission of Electricity from Hot Bodies," rev. ed., Longmans, Green & Company, New York, 1921.

when one pair of the two diode portions is used. This will be found to be true in all multiple-section diodes.

h. The absence of plate-current saturation points similar to those appearing in figures 29 and 30 is due to the use of oxide-coated emitters in this tube. An application as low as 32 volts to the plate results in a fairly high value of plate current, almost 70 ma. Judging by the shape of the characteristic, the saturation point is a long way off. The tube probably would be damaged long before the plate-current curve would flatten because of the application of sufficient plate voltage to attract all the emitted electrons. This does not mean that diodes are not used at plate voltages exceeding 32 volts; they are used with very high voltages, many tens of thousands of volts, but when so used, diodes are specially designed.

25. A-c Plate Resistance of Diode

a. The a-c plate resistance of the diode is defined as the resistance of the path between cathode and plate to the flow of *an alternating current* inside the tube. Such is the definition meant when the term *resistance* is used without qualification for the diode and all other electron tubes. As will be seen later, it is an important term and is closely related to operating conditions.

b. The a-c plate resistance is the ratio of a small change in plate voltage by the corresponding change in plate current. Expressed in an equation

$$r_p = \frac{\Delta e_p}{\Delta i_p}$$

in which r_p is the a-c plate resistance in ohms, Δe_p represents a small change in plate voltage, and Δi_p represents a corresponding small change in plate current caused by the plate voltage change. The Greek letter Δ signifies a *small change of*.

c. Figure 33 shows a plate-current plate-voltage characteristic curve identical to the one in B of figure 32 and obtained from the circuit in A of figure 32, where one section of a 6H6 diode is used. To establish the *a-c resistance* at any point along the curve, the plate voltage is varied on both sides of it at some definite value. B of figure 32 shows that the d-c plate resistance, R_p for this diode is 500 ohms when the plate voltage is held constant at 20 volts dc. Suppose it is desired to find the a-c resistance when the mean value of this assumed a-c voltage is 20 volts, and the variation or *swing* is arbitrarily chosen at 1.6 volts on either side of the 20-volt point; that is, when Δe_p equals 3.2 volts (fig. 33).

d. To compute r_p, the change in plate current for the given change in d-c plate voltage first must be found from the curve. At 21.6 (20 plus 1.6) volts, the plate current is 45 ma or .045 ampere. At 18.4 (20 minus 1.6) volts the plate current is 35 ma or .035 ampere. These provide the two limits of voltage and current. Consequently,

$$r_p = \frac{\Delta e_p}{\Delta i_p} = \frac{21.6 - 18.4}{.045 - .035} = \frac{3.2}{.010} = 320 \text{ ohms.}$$

e. The value of 320 ohms given above is the a-c plate resistance for a plate voltage which varies between 18.4 and 21.6 volts, whereas the same point is equal to a d-c plate resistance of 500 ohms when the plate voltage is held constant at 20 volts. Using the same method, 278 ohms a-c plate resistance is obtained at the 28-volt plate-voltage point for a change in plate voltage of 1.6 volts each side of the mean value of 28 volts, whereas the d-c resistance is 422 ohms when the plate voltage is maintained constant at 28 volts. Similarly, r_p is shown equal to 527 ohms when the 8-volt plate-voltage point varies *1* volt on either side of the 8-volt mean value. If 1.6 volts is used in the latter case instead of 1 volt, r_p still remains relatively close to 527 ohms. However, it must be kept in mind that the smaller the change in plate voltage, the more accurate are the results. This is because of the nonlinearity of the characteristic curve about this small change. In the former two cases, the curve is fairly linear and 1.6 volts are used arbitrarily. Normally, for linear operation, the operating point for this curve is chosen with an r_p equal to about 320 ohms.

f. It can be seen that an appreciable difference exists between d-c plate resistance and a-c plate resistance, the latter being approximately one-half of the former. This is, in general, true for all types of vacuum tubes. Furthermore, as figure 33 shows, the a-c resistance also is related to the plate voltage, *decreasing* as plate voltage is *increased*, and *increasing* as plate voltage is *decreased*. The *exact value of a-c resistance depends on the point of operation se-*

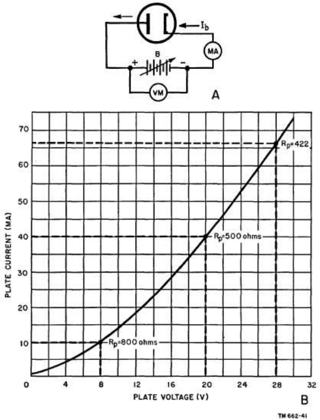


Figure 32. Plate-current plate-voltage characteristic for type 6H6 tube, using only one diode section.

as the plate voltage increases, and *increases* as the plate voltage is decreased. It has a nonlinear behavior. If the relationship of plate voltage and plate current were linear over the entire range of plate voltage, the plate-current curve would be a straight line instead of having a curved characteristic. A straight line would indicate that the d-c plate resistance remained constant over the full range of plate voltage.

g. Another significant fact in connection with the $E_b = I_b$ characteristic curve is the condition resulting when the two sections of this duo-diode are connected in parallel, and the two cathodes also are joined in parallel. The plate current in this case becomes twice the amount obtained when the same value of plate voltage is applied to a single pair of elements. Accordingly, the values at any point along the plate-current curve are doubled when both sections of the duo-diode are paralleled. The plate resistance, therefore, becomes half of that existing

having the requisite velocity. Thermionic emission of electrons therefore increases with increase of temperature and with reduction of electron affinity. Measurable emission is observed at temperatures above 1000°K.

Electrons that escape will have resultant velocities made up of the excess perpendicular to the surface, plus the original components parallel to the surface, which are not altered by the surface forces. If the emitted electrons are not drawn away by an external field, they will form a space charge, the individual particles of which are moving about with random velocities. Because the initial average normal velocity of the electrons after emission is away from the surface and because of the mutual repulsion of like charges, electrons drift away from the surface. Collisions between electrons cause some of them to acquire velocity components toward the emitter, where they may reenter the surface with a gain of kinetic energy equal to the electron affinity. Another factor responsible for the return of electrons to the emitter is the electrostatic field set up by the negative space charge and, if the emitter is insulated, by the positive charge that it acquires as the result of loss of electrons. This field increases with the density of space charge, and equilibrium is established when only enough electrons can move away from the surface to supply the loss by diffusion of the space charge. If diffusion can then be prevented, just as many electrons return to the metal in unit time as leave it. Figure 2-1 gives a rough picture of the electron distribution under equilibrium conditions.

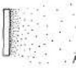


Fig. 2-1.—Distribution of electrons near an emitting surface.

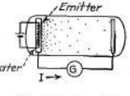


Fig. 2-2.—Flow of anode current as the result of diffusion of electrons from cathode to anode without the application of anode voltage (Edison effect).

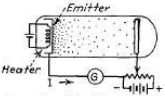


Fig. 2-3.—Use of anode voltage to increase anode current.

If a second, cold electrode is placed near the emitting surface in vacuum and connected to the emitter through a galvanometer, as shown in Fig. 2-2, the meter will indicate the small current resulting from the drift of electrons from the emitter to the second electrode. These electrons return to the emitter through the galvanometer and prevent the emitter from becoming positively charged. This phenomenon, first observed by Edison, is called the *Edison effect*. When the second electrode is made positive with respect to the emitter by the addition of a battery, as shown in Fig. 2-3, the current is increased. As the voltage is gradually raised, it is found that at any emitter temperature there is a more or less definite voltage beyond which the current is nearly constant, all emitted electrons being drawn to the collector. This current is called the *saturation current*, and the corresponding voltage, the *saturation voltage*. The lack of increase of current beyond saturation voltage is spoken of as *voltage saturation*. Saturation current varies with the temperature and electron affinity of the emitter. The negative emitter in Fig. 2-3 is called the *cathode;* and the positive collector, the *anode* or *plate*. An electron tube containing only a cathode and an anode is called a *diode*. Although the electrons move from cathode to anode, the current, according to convention, is said to flow from anode to cathode within the tube.

2-2. Richardson's Equation.—By means of classical kinetic theory, and by thermodynamic theory, Richardson derived two slightly different equations for saturation current as a function of temperature.[1] It is not possible experimentally to determine which of Richardson's equations is correct, but this was later done theoretically by M. v. Laue, S. Dushman, and A. Sommerfeld. The equation that is now believed to be correct is

$$I_s = AT^2\epsilon^{-w/kT} \qquad (2\text{-}1)$$

in which I_s is the saturation current per unit area of emitter, T is the absolute temperature, w is the electron affinity of the emitter, k is Boltzmann's universal gas constant, and A is a constant, probably universal for pure metals. The value of k is 8.63×10^{-5} volt/deg and the theoretical value of A for pure metals is 60.2. The form of the curve that represents Richardson's equation, shown in Fig. 2-4, is determined practically entirely by the exponential factor.

It is important to note that Richardson's equation holds only for the saturation current and that the anode voltage must,

[1] RICHARDSON, *loc. cit.*

considerably larger, since the plate current is larger, than that of the tungsten types. Oxide-coated emitters release so many electrons that it is practically impossible to find plate voltages which will draw off all of these electrons without ruining the tube. Consequently, most modern tubes which use oxide-coated cathodes do not display a plate-voltage saturation characteristic, but rather show continually rising plate-current curves as the plate voltage is increased as shown in figure 31. Note from the curves that as the operating temperature of the cathode increases, the plate current increases. In addition, this increase will have a more noticeable effect on the oxide-coated cathodes since the solid and dashed lines are much farther apart in the higher operating temperatures than in the lower ones.

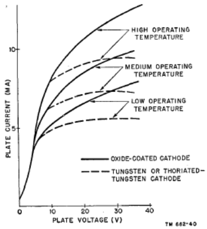


Figure 31. Plate-current emitter-temperature characteristic curves of diode with different types of emitters.

24. D-c Plate Resistance of Diode

a. Since the application of a positive voltage to the plate of a diode results in the flow of plate current, and since some form of control of the magnitude of plate current for different values of voltage exists in the tube, it is entirely proper to view the current control mechanism, whatever may be its nature, as being the equivalent of a resistance. Electrical fundamentals teach that the control of current in a system issues from some form of opposition to the current flow present in the system.

b. Such opposition exists in all electron tubes, among which is the diode. It stems from many factors, such as the spacing between the electrodes, their physical size, the conditions of emission, the conditions of the space charge, and, in general, the energy wasted while the electrons are traversing the space within the tube. Tube resistance is of two kinds: *d-c plate resistance* and *a-c plate resistance*, each of which will be explained. The former usually is symbolized as R_p and the latter as r_p.

c. The d-c plate resistance of the diode is that opposition to plate current flow offered by the tube when a d-c voltage is applied to the plate. It can be calculated from Ohm's law, $R=E/I$, with the plate voltage and the plate current inserted as the known factors in the equation.

d. Referring to figure 32, B shows a typical plate-current plate-voltage characteristic for a type 6H6 duo-diode tube, using only one pair of the two pairs of elements contained inside the envelope—that is one cathode and its associated plate. With 8 volts dc applied to the plate, in A, the plate current, I_b, is seen to be 10 ma, or .01 ampere. (The notation E_b is used as the varying constant voltage between the plate and cathode. This may or may not be the same value as E_{bb}.) Applying Ohm's law for d-c circuits, these values of plate voltage and plate current represent a d-c plate resistance of

$$R_p = \frac{E_b}{I_b} = \frac{8}{.01} = 800 \text{ ohms.}$$

e. Similarly, with 20 volts dc applied to the plate, the curve shows a plate current of 40 ma, or .04 ampere. This corresponds to a d-c resistance of $20/.04 = 500$ ohms. With 28 volts dc applied to the plate, the plate current on the curve is 66.4 ma or .0664 ampere, and the d-c resistance is $28/.0664 - 422$ ohms.

f. Examination of these figures, and also of the shape of the characteristic curve, shows that the resistance offered by the diode to the flow of plate current is *not* constant, as is ordinarily the case when resistance is present in a conventional d-c circuit. The characteristic shows that the resistance of the diode *decreases* therefore, be high enough at all times so that all emitted electrons are drawn to the anode. If the anode voltage is fixed at some value E_1, while the temperature is raised, then at some temperature the current will begin to be limited by space charge in a manner similar to that when there is no accelerating voltage. Further increases of temperature will then have no effect upon the current. This temperature is called the *saturation temperature*, and the failure of the current to increase at higher temperature is spoken of as *temperature saturation*. If the emitter were homogeneous and the electrostatic field constant over the surface of the emitter, the advent of saturation would be abrupt, as indicated at point A. Actually, because of variations of temperature and electron affinity and of electrostatic field, saturation does not take place over the whole cathode surface at the same temperature, and so experimentally determined curves bend over gradually, as shown by the dotted curves. At higher anode voltage E_2, saturation occurs at a higher temperature. If the voltage is increased with temperature, then the current will continue to rise with temperature until the temperature becomes sufficiently high to vaporize the emitter.

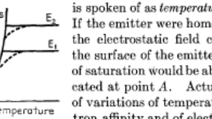


FIG. 2-4.—Curves of anode current *vs.* emitter temperature at two values of anode voltage. The left-hand curve, I_s, represents saturation emission current.

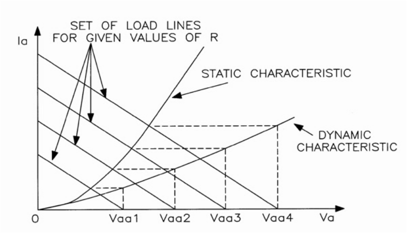
Since only those electrons which have relatively high energies can escape from the metal, thermionic emission necessarily results in the reduction of the average energy of the remaining electrons and molecules, and hence of temperature of the emitter. Heat must be supplied continuously to the emitter in order to prevent its temperature from falling as the result of emission. The cooling effect of emission current is plainly visible in filaments in which the emission current is comparable with the heating current, as in the type 30 tube.

Richardson's equation shows that the emission current which can be obtained at any temperature varies inversely with the electron affinity. Because of the exponential form of the equation, small changes in temperature or electron affinity result in large changes of emission current. A 15 per cent reduction of electron affinity produces an eight- or tenfold increase of emission over the working range of temperature. The ratio of the emission current in milliamperes per square centimeter to the heating power in watts per square centimeter is called the *emission efficiency*. Emission efficiency increases with decrease of electron affinity.

A satisfactory practical source of thermionic emission must satisfy two requirements: it must have a high emission efficiency, and it must have a long life. Thermal losses can be reduced by proper design of the emitter and by reduction of emitter temperature. (Cathodes of special design, which give very low thermal losses, can be used in gaseous discharge tubes. These will be discussed in Sec. 9-14.) The life of an emitter increases with the difference between the normal operating temperature and the vaporization or melting temperatures of the metal or metals of which it is constructed. Since low operating temperature is made possible by low electron affinity, it is evident that the choice of emitters of low electron affinity is favorable to long life, as well as to high efficiency.

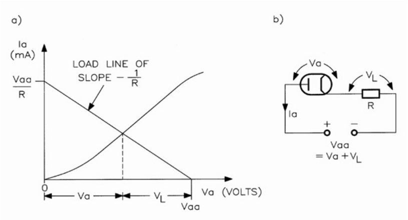
2-3. Pure Metallic Emitters.—Pure metals having low electron affinities, such as the alkali metals or calcium, cannot be used as emitters in electron tubes because they vaporize excessively at temperatures at which appreciable emission is obtained. Only two pure metals, tantalum and tungsten, are suitable for use as practical emitters. Although the electron affinity of tantalum is lower than that of tungsten, tantalum is more sensitive to the action of residual gases and has lower vaporization temperature. Tantalum is therefore seldom used. Pure metallic emitters are now used only in large high-voltage (above 3500 volts) power tubes, in which they are found to have longer life than the special emitters which are used successfully in small tubes.

2-4. Thoriated Tungsten Emitters.—The presence of impurities in a metal may produce a marked change in the value of its electron affinity. This is usually attributed to the formation of thin layers of these impurities at the surface. Such a layer may produce very high fields at the surface by virtue of the fact that it may be electropositive or electronegative relative to the main metal. Thus the presence of an absorbed layer of oxygen, which is electronegative with respect to tungsten, results in a field that opposes the emission of electrons and therefore increases the electron affinity of tungsten. The presence,



Obtaining the dynamic characteristic for a diode valve and its load.

The points on the dynamic characteristic are obtained by projecting, horizontally, the intersection of a load line and the static characteristic until it in turn intersects a vertical line drawn from a supply voltage value. Since the dynamic characteristic is drawn for a range of values of the supply voltage, this implies that the latter is varying, in other words it is an alternating supply rather than DC, as is the case in rectification.



(a) The load line for a diode valve. (b) the diode in series with a linear resistive load.

The second image shows the diode in series with its load and defines the voltages and currents in question. A 'load line' of slope -l/R is drawn between the two points: Ia = Vaa/R Va = 0 and Ia = 0, Va = Vaa. As in solid state practice, the end points of a load line define zero conduction and maximum conduction, the latter being dependent upon the values of supply voltage and load resistance. Any other points on the load line imply intermediate levels of conduction. By dropping a construction line from the intersection of the load line and the static characteristic, we can see how the total supply voltage Vaa is divided into the two separate voltages Va (the voltage across the diode) and Vl (the voltage across the load).

The Dynamic Characteristic

By taking a number of different values of supply voltage Vaa (as would happen if the supply was alternating, for example) and assuming a constant value for the load Rl then, by drawing a separate load line for each value of supply voltage, the dynamic characteristic can be obtained, as shown below.

on the other hand, of a monatomic layer of thorium atoms or ions on the surface of tungsten reduces its electron affinity remarkably. It is of interest to note that the electron affinity of thoriated tungsten may be even lower than that of pure thorium (see Table 1-II).

The reduction of the electron affinity of tungsten as the result of introduction of small amounts of thorium was first observed by Langmuir in 1914 in the course of a study of the properties of tungsten filaments.[1] Thorium oxide is introduced into tungsten during the process of manufacture in order to improve its physical properties. Subsequent high temperature converts a portion of the thorium oxide into metallic thorium, which diffuses to the surface. Investigations by Dushman, Becker, and others[2] indicated that the lowest value of w and the highest value of the constant A in Richardson's equation are obtained when the tungsten is completely, or perhaps very nearly, covered with a single layer of thorium atoms.

Thoriated tungsten shows no increase of emission over that of pure tungsten until it is *activated*. The activation process is performed after evacuation of the tube. It consists first in "flashing" the emitter for a few moments at a temperature of 2500 to 2800°K. This high temperature reduces some of the thorium oxide to thorium. The temperature is then kept for some minutes at about 2200°K, which allows the metallic thorium to diffuse to the surface. The best value of diffusing temperature is determined by the rates of diffusion of thorium to the surface, and of evaporation from the surface. If the temperature is too high, the evaporation exceeds the diffusion, resulting in deactivation. The emitter is normally operated at temperatures that do not exceed 2000°K, which is sufficiently low so that evaporation of thorium from the surface is negligible. If the emitter is accidentally operated at such a high temperature that the whole supply of thorium diffuses to the surface and evaporates, it can be reactivated by repeating the original activation process. This may be done several times before all the thorium oxide is used up.

[1] LANGMUIR, I., *Phys. Rev.*, **4**, 544 (1914).
[2] DUSHMAN, S., and EWALD, J., *Phys. Rev.*, **29**, 857 (1927); BECKER, J. A., *Trans. Am. Electrochem. Soc.*, **55**, 153 (1929).

A useful tool in the study of the phenomenon of activation is the "electron microscope."[1] This consists of the emitter and means for accelerating the electrons and for focusing them upon a screen[2] which fluoresces under the impact of electrons. It has been shown that the action of electromagnetic and electrostatic fields upon electron beams is similar to the action of lenses upon light.[3] Thus it is possible to obtain on the screen a sharp enlarged image which shows clearly the individual points of emission of the cathode.[4] Similar results are achieved by use of a straight filament at the axis of a cylindrical glass tube, the inner surface of which is covered with a fluorescent material.[5] The coated surface, which acts as the anode, is maintained at a positive potential of several thousand volts by means of a wire helix coiled inside the tube in contact with the coating. Electrons emitted by the filament are attracted radially toward the anode coating, where they produce a magnified image of the electron emission at the surface of the filament. Figure 2-5 gives a series of photographs of the screen of such a tube, showing the activation of thoriated tungsten. (The bright vertical line is caused by light from the filament, and the dark lines by the shadow of the helix.)

The presence of even small amounts of gas has a very destructive effect upon a thoriated tungsten emitter. This may result either from direct chemical action, such as oxidation, or from the removal of thorium from the surface by the bombardment of positive ions. The sensitiveness of thoriated emitters to the

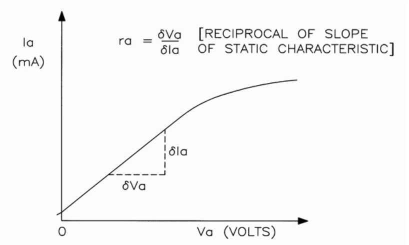
[1] KNOLL, M., and RUSKA, E., *Ann. Physik*, **12**, 607 (1932). The electron microscope has many applications besides that mentioned here. Recent instruments may be used in place of ordinary microscopes in the study of matter and give higher magnification than can be attained with light. For a survey and a bibliography of this subject, see R. P. Johnson, *J. Applied Physics*, **9**, 508 (1938).

[2] See, for instance, I. G. Maloff and D. W. Epstein, "Electron Optics in Television," McGraw-Hill Book Company, Inc., New York, 1938.

[3] BUSCH, H., *Ann. Physik*, **81**, 974 (1926); MALOFF, I. G., and EPSTEIN, D. W., *Proc. I.R.E.*, **22**, 1386 (1934); EPSTEIN, D. W., *Proc. I.R.E.*, **24**, 1095 (1936); MALOFF and EPSTEIN, *loc. cit.*

[4] See, for instance, E. Brüche and H. Johannson, *Ann. Physik*, **15**, 145 (1932); M. KNOLL, *Electronics*, September, 1933, p. 243.

[5] JOHNSON, R. P., and SHOCKLEY, W., *Phys. Rev.*, **49**, 436 (1936). See also *Electronics*, January, 1936, p. 10, March, 1937, p. 23.



and is the value of resistance obtained by dividing a small change in anode voltage by the corresponding change in anode current. It is therefore the reciprocal of the slope of the static characteristic, and varies with the operating point, although fairly constant over much of the space charge limited region. This is a real value of resistance, since it represents the opposition of the valve to alternating quantities.

Series Circuit Operation

It is usual to operate a diode valve, which is clearly a non-linear device, in series with a resistive load, the latter being a linear device. It is possible to predict how the voltages and current in the circuit will vary by using a graphical construction.

Above three curves have been drawn for different values of cathode temperature, although in practice, as explained earlier, the cathode is held at a constant temperature.

It is interesting to note that:

A) The current is not exactly zero when the anode voltage is zero, but has a value (Iao) of a few micro-amperes. This is known as the 'splash current' and is the result of a few high energy electrons that manage to cross the inter-electrode gap even without an attracting potential.
B) In the space-charge limited region, the characteristic is nearly linear (actually following the 'three-halves' power law: Ia is proportional to Va-3/2).
C) In the temperature limited region there is little change in la even though there are large changes in Va. This is because the anode is collecting electrons at the same rate as they are being emitted by the cathode.
D) No significant current flows when the anode is negative with respect to the cathode.

The Anode Slope Resistance ra

It is worth introducing this parameter at this time since it is one that we shall make use of later in discussing the performance of more complex valves. It is defined as shown below,
Defining anode slope resistance for a diode valve.

action of gases and the rate of evaporation of thorium may be greatly reduced by heating the emitter in an atmosphere of hydrocarbon vapor, which causes the formation of a shell of

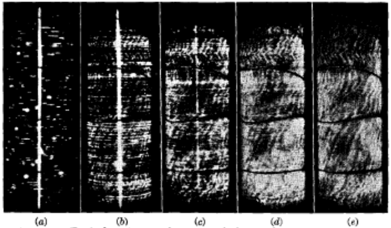


FIG. 2-5.—Typical activation behavior of thoriated tungsten. Image (*a*) immediately after 10 seconds at 2800°K, (*b*) after additional 4 minutes at 1850°K, (*c*) after 20 minutes at 1850°K, (*d*) after 30 minutes at 1850°K, (*e*) after 70 minutes at 1850°K. All pictures made at 1200°K. The decreasing exposure time is evidenced by reduction of apparent brilliance of the filament. (*Courtesy of R. P. Johnson.*)

tungsten carbide. Because of the reduction of the rate of evaporation of the thorium, a carbonized emitter can be oper-

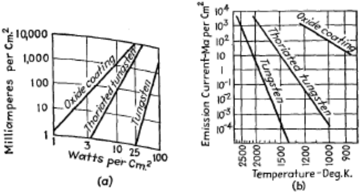


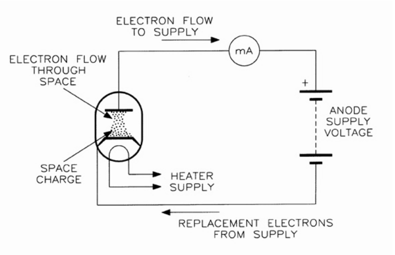
FIG. 2-6.—*a*. Curves of emission current *vs.* heating power. *b*. Curves of emission current *vs.* emitter temperature.

ated at a much higher temperature, with consequent increase of emission current and efficiency. At this higher temperature the increase of diffusion makes possible the continuous replacement of thorium removed from the surface by the action of gas molecules or ions. Figure 2-6 shows that the emission efficiency of thoriated tungsten is much higher than that of pure tungsten and that a given emission may be obtained at a much lower temperature. Because of the lower electron affinity, higher emission efficiency, and longer life of oxide-coated emitters, thoriated tungsten emitters are now used very little in receiving tubes.

2-5. Oxide-coated Emitters.—By far the most widely used emitters in small high-vacuum tubes are oxide-coated emitters, first used by Wehnelt.[1] Although the process of manufacture of oxide-coated cathodes varies considerably, it consists, in general, in coating a core metal, usually nickel or alloys of nickel and other metals, with one or more layers of a mixture of barium and strontium carbonates. The carbonates may be suspended in water, although a binder such as collodion or a mixture of one part of Zapon varnish in 20 parts of amyl acetate is usually used. The mixture may be applied to the core by spraying or by dipping or dragging the core through the mixture. When a thick coating is desired, the mixture is applied preferably in the form of several thin coatings heated sufficiently between applications to burn out the binder. After application of the carbonate coating, the emitter is mounted in the tube, which is then evacuated, and the emitter is heated electrically to a temperature of about 1400°K. The high temperature reduces the carbonates to oxides, the liberated carbon dioxide being removed by the pumps. The temperature is then lowered somewhat and voltage is applied to the anode for some time, during which the emission builds up to its proper value. The normal operating temperature is in the range from 1000 to 1300°K.

Many experiments have been performed to determine what takes place during the activation process and from which part of the emitter electrons are emitted. Reduction of the oxides to pure metal may result from chemical reaction, from electrolysis of the oxides, or from the bombardment of positive ions formed in the gas between the anode and the emitter by electrons

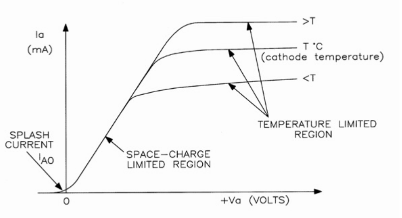
[1] WEHNELT, A., *Ann. Physik*, **14**, 425 (1904). For an excellent review of the subject of oxide-coated emitters see J. P. Blewett, *J. Applied Physics*, **10**, 668 and 831 (1939).



The flow of current in a diode valve.

Diode Static Characteristics

We now start getting into the ways in which specifications for thermionic devices are presented. For the diode, these illustrate clearly the dependence of anode current upon anode voltage.



The static characteristic of a diode valve.

Since electrons are negative charged particles, they will only be attracted to the anode if this is given a positive potential with respect to the cathode. This explains why the valve only conducts in one direction, from cathode to anode, and not vice versa. It also explains the choice of the word 'valve' to describe the device, since a valve is, by definition, a one-way device. The Americans, however, never cottoned on to this terminology and always refer to them as 'vacuum tubes'.

The magnitude of the current flowing in a diode depends upon the number of electrons emitted and the magnitude of the voltage applied to the anode (known as the anode voltage Va). The amount of electron emission depends upon the temperature of the cathode, which is fixed by the voltage supply to the heater, this being a constant value. The only true variable is, therefore, the anode voltage. The action of the latter in controlling the anode current can be explained as follows.

As we now know from the foregoing, the cathode is normally surrounded by a cloud of electrons known as the space charge. With zero anode voltage there is no current flow, and there is a state of equilibrium between the electrons being emitted and those falling back onto the cathode's surface, The application of a small positive voltage to the anode causes some of the space charge electrons to be attracted to the anode, resulting in a small anode current flow. The gaps created by these electrons leaving the space charge are filled by further emission from the cathode. Electrons arriving at the anode flow to the positive supply terminal, while at the same time an equal number of electrons leave the negative supply terminal for the cathode. This gives rise to a continuous current flow around the circuit, which may be detected by an ammeter placed in, say, the anode lead. The picture below shows an illustration of this.

accelerated by the applied field. Perhaps all three of these processes occur. Free metal formed throughout the oxide diffuses toward the surface. Although particles of free metal are distributed throughout the coating in a completed emitter, most recent evidence appears to indicate that the emission takes place at the outer surface.

Examination of Fig. 2-6 shows that the emission efficiency of an oxide-coated emitter is even higher than that of thoriated tungsten. The low temperature at which an oxide-coated cathode can be operated is an advantage in some applications.

The emission from oxide-coated cathodes is reduced or destroyed by the presence of gases, due to oxidation of the active metal or to removal of the active metal or even the complete coating by positive-ion bombardment. Another cause of damage to oxide-coated cathodes is the development of hot spots. Because of nonuniform activation of the emitter, emission is not uniform over the surface. The flow of emission current through the oxide coating, which has high resistance, raises its temperature. Since the temperature rise is greatest at points of the cathode at which the emission is high, the emission increases still more at these points. If the current is not limited by space charge, the action may become cumulative and the current and temperature increase to such an extent that the coating is removed. In filamentary cathodes the local rise in temperature may be so great as to melt the filament. Hot spots are most likely to occur at high anode voltages. This is one reason why oxide-coated emitters are not used in high-voltage tubes.

When full emission current is drawn from an oxide-coated emitter the current first falls rapidly and then slowly approaches a steady value. This decay of current is thought to be caused by electrolytic removal of barium from the surface or by electrolytic deposition of oxygen on the surface. The initial emission is recovered if the emitter is heated without the flow of space current. The useful life of oxide-coated emitters, which is several thousand hours, is terminated by a rather sudden decay in emission to a very low value. This may be caused by evaporation of free barium and of the supply of barium oxide that furnishes free barium during the active life of the emitter. The useful life of a vacuum tube containing an oxide-coated cathode may also be terminated by the liberation of gas from the emitter.

2-6. Cesiated Tungsten Emitters.—A fourth type of emitter, not used commercially in thermionic tubes, is produced by depositing a monatomic layer of cesium on tungsten. Because the ionizing potential of cesium vapor is less than the electron affinity of tungsten, the tungsten removes an electron from a cesium atom which strikes it, leaving a positive ion which is held to the tungsten surface by the resulting electrostatic field. The force of adhesion is even greater if the tungsten is first covered with a monatomic layer of oxygen, which is electronegative with regard to tungsten. The strong electrostatic field between the cesium ions and the tungsten or oxygen reduces the electron affinity to the comparatively low value of 0.7 electron volt or less. Because cesium melts at a temperature only slightly above room temperature, the cesium vapor is obtained by merely introducing a small amount of cesium into the evacuated tube, the subsequent vaporization being sufficient to coat the filament.

The low electron affinity of the tungsten-oxygen-cesium emitter makes possible high emission currents at a temperature of only 1000°K. This type of emitter has several disadvantages, however, which make it impractical for use in commercial tubes. As the result of the high vapor pressure of cesium at operating temperatures of the tube, the characteristics of the tube are influenced by tube temperature. Too high temperature vaporizes the cesium, causing temporary reduction in emission, or even removal of the oxygen layer with permanent reduction of emission. Except at very low anode voltages, ionization of the cesium vapor occurs, resulting in fluctuations of anode current. The presence of positive ions is also detrimental to the action of amplifier tubes for other reasons, which will be discussed (Secs. 2-8, 6-5, 10-16).

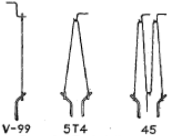


FIG. 2-7.—Typical filamentary cathodes. (*Courtesy of Radio Corporation of America.*)

2-7. Mechanical Construction of Cathodes.—Cathodes used in high-vacuum thermionic tubes are divided into two general classes, filamentary and indirectly heated. Figure 2-7 shows the form of typical filamentary cathodes. Early vacuum tubes used only filamentary cathodes. When filamentary cathodes are operated on alternating current, the stray alternating

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Valve Technology - A Practical Guide
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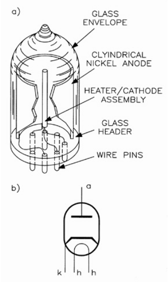
The Diode Valve

The diode valve is so called because it has just two electrodes – the cathode and the anode.



(a) Construction of a modern diode valve (indirectly heated type), (b) circuit symbol for a diode valve.

These correspond to the two electrodes of the original diode valve mentioned above, the cathode being the electrode that is heated and emits electrons, and the anode being the electrode that collects the electrons (notice also that these terms have passed forward into semiconductor phraseology - cathode, anode, emitter, collector!).

electrostatic field and the alternating voltage across the filament cause an alternating component of plate current that may be objectionable in amplifiers in which several tubes are used in succession. This difficulty led to the development of the indirectly heated, or *heater-type*, cathode. In addition to the unipotential emitting surface and freedom from large stray fields, the heater-type cathode has the advantage that a single source of power may be used to heat a number of cathodes between which a difference of potential must exist.

Indirectly heated cathodes used in receiving tubes consist of an oxide-coated cylindrical sleeve, usually of nickel, within which is some form of heater. The most common types of heaters are illustrated in Fig. 2-8. The 5Z4 and 25A6 heater coils are helically wound. That of the 6K7 type of cathode is wound in a reverse helix. After being wound and formed, the coils are coated with a refractory insulating material and inserted into the sleeve. The heater of the 25L6 type of cathode is covered with a refractory insulating coating of sufficient adherence to permit the wire to be bent into the desired shape after it has been coated. Because of the small magnetic field produced by the 6K7 type of heater, there is very little 60-cycle plate-current variation, or "hum," when the heater is operated on alternating current. The return type of helical heater exemplified by the 25A6 heater and the folded type of heater used in the 25L6 cathode make possible the use of enough wire for 25-volt operation. The advantage of the 25L6 construction is its low cost. More complicated cathode structures used in arc-discharge tubes will be discussed in Chap. 9.

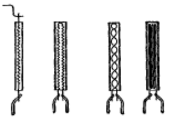


FIG. 2-8.—Structure of typical heater-type cathodes. (*Courtesy of Radio Corporation of America.*)

2-8. Effects of Gas upon Emission and Space Currents.—The deleterious effects of gas upon emitters of various types as the result of chemical action, absorption of thin layers of gas upon the surface, and positive-ion bombardment have already been mentioned. If the anode voltage is sufficiently high to produce ionization of the gas, other effects become apparent. If anode current is at first limited by space charge, the appearance of positive ions tends to neutralize the negative space charge surrounding the filament, thus increasing the anode current. If the voltage is high enough to give saturation current initially, then increase of current occurs because the electrons and ions produced by bombardment of neutral gas molecules by the emitted electrons add to the current. Unfortunately this increase of current is likely to be accompanied by a number of undesirable effects. Currents through ionized gases usually fluctuate, resulting in "noise" in tubes used for amplification. The relatively low velocity of positive and negative ions produces a lag in the response of current to changes of voltage. Variations of gas pressure resulting from changes of temperature or from the absorption or emission of gas from the walls and electrodes may cause the characteristics of the tube to vary. Finally, in a gassy tube, positive-ion current flows to an electrode to which a negative voltage is applied. When the anode current is controlled by means of a negative voltage applied to an electrode through a high resistance, the flow of positive-ion current through the resistance may cause an objectionable voltage drop and, under certain circumstances, may even result in damage to the tube (see Secs. 6-5, 9-17, and 10-16).

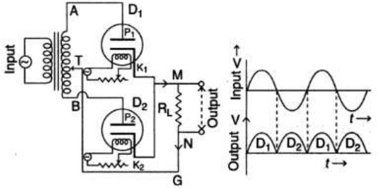
In the manufacture of high-vacuum tubes, many precautions are taken to ensure the removal of gas from walls and electrodes. The electrodes are thoroughly cleaned and are then heated for several minutes in an atmosphere of hydrogen, which removes oxygen and water vapor. After the tube is assembled and connected to the pumps, the electrodes are heated to about 800 or 1000°C by high-frequency induction in order to remove other occluded gases. Residual gas is removed by the use of *getters*, which are active chemical substances such as barium, magnesium, aluminum, and tantalum, having the property of combining with gases when they are vaporized. In glass tubes a small amount of the getter is mounted in such a position that it will be heated and vaporized or "flashed" during the inductive heating of the elements. By proper location of the getter, the vapor can be prevented from condensing in places where it might cause electrical leakage or undesirable primary or secondary emission. The effectiveness of the getter results not only from its chemical combination with gases during flashing, but also from subsequent absorption of gases by getter that has condensed on

2. A rectifier is always followed by electronic circuits called filter circuits which allow only D.C. to pass through them and by pass the A.C. Thus a rectifier-filter combination gives a D.C. output.

Applications of Diode

The two main applications of diode are :

(a) As a rectifier (b) As a detector



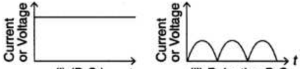
(i) Circuit (ii) Input-Output waveforms

positive. Therefore, the second diode conducts but the first remains passive. Thus, the two diodes conduct alternately. But in both half cycles of A.C., the current in load resistance R_L flows in the same direction. So, we get continuous D.C. at output. For full-wave rectifier,

Note :	$I_{D.C.} = \frac{2I_0}{\pi}$
	$I_{rms} = \frac{I_0}{\sqrt{2}}$
	$\eta_{max} = 81{\cdot}2\%$
Ripple factor,	$r = 0{\cdot}48$

The output of rectifier is fluctuating or pulsating. To make it smooth, filters are used.

Notes : 1. The output obtained from a half wave or full wave rectifier is not a pure D.C. but it is a pulsating D.C. (mixture of A.C. and D.C.)



(i) (D.C.) (ii) Pulsating D.C.

the walls of the tube. The action of the getter during flashing is increased by ionization of the gas by means of voltages applied between the electrodes or by the radio-frequency field of the induct on heater. To ensure the removal of gas from the walls, tubes are baked during the process of manufacture. On machines that exhaust and seal the tubes separately, the bulbs are heated in ovens during exhaustion. On "Sealex" machines, the tubes are sealed and exhausted on the same machine, the heat from sealing being used to drive gases from the bulbs during exhaustion.

In tubes with metal envelopes, the shielding action of the shell makes it impossible to heat the electrodes and the getter by induction. The electrodes may be heated by radiation from the shell, which is heated by gas flames. Although the getter may be fastened to the inside of the shell and vaporized by heating the shell locally, another method has been developed that requires less critical control.[1] A short length of tantalum ribbon, which connects the shell to its terminal pin in the base, is coated with a mixture of barium and strontium carbonates. While the tube is on the pumps, the temperature of the tantalum wire is raised electrically to about 1100°C. This converts the carbonates into oxides. After the tube has been sealed off, the tantalum wire is heated to a temperature in excess of 1200°C. This causes the tantalum to reduce the oxides to pure metallic barium and strontium, which vaporize. Since the vapor moves in straight lines, it can be directed as desired by means of shields and by proper location of the tantalum wire. This type of getter is called *batalum* [See (11) in Fig. 3-11*b*].

2-9. Limitation of Anode Current by Space Charge.—The effect of space charge in limiting space current and the increase of anode current resulting from an accelerating anode potential have already been mentioned in connection with the theory of thermionic emission. Before proceeding to a discussion of the quantitative relation between anode current and anode potential in a two-element tube, it is of interest to discuss further the physical picture underlying the phenomenon. The behavior of the emitted thermionic electrons is complicated by their initial velocities. For this reason it is best first to formulate a theory

[1] LEDERER, E. A., and WAMSLEY, D. H., *RCA Rev.*, **2**, 117 (1937). This article also discusses gettering methods used in glass tubes.

on the assumption that the initial velocities are zero and then, when they are taken into consideration, to see in what manner the results should be altered. For the present, therefore, initial velocities will be assumed to be zero. It will be further assumed that both cathode and anode are homogeneous, constant-potential, parallel planes of large area, and hence that the electric field over the surface of the cathode may be assumed to be uniform.

Electrons that leave the cathode constitute a space charge that exerts a retarding field at the cathode. The net field at the surface of the cathode is the difference between this retarding field and the accelerating field produced by the positive voltage of the anode. The number of electrons in the space, and hence the retarding component of field at the cathode, increases with the anode current. When the positive anode voltage is applied, the anode current builds up with great rapidity to such a value that the average retarding field at the cathode caused by the space charge is equal to the accelerating field caused by the anode voltage, making the average field zero at the cathode. Increase of emission then does not raise the anode current, as the additional emitted electrons merely reenter the cathode. If it were possible in some manner to increase the density of space charge by increasing the current beyond this equilibrium value, or if the anode voltage were reduced slightly, then the net field at the cathode would be a retarding one. For an instant, all emitted electrons would be prevented from moving away from the cathode, and the current and space-charge density would be automatically reduced to a value that would again make the average field at the cathode zero. An increase of anode voltage causes the accelerating field to exceed the retarding field. The number of electrons moving to the anode then increases until the retarding field again equals the accelerating field.

At first thought it may not seem plausible that there can be a steady flow of electrons to the anode when both the velocities of emitted electrons and the average electrostatic field are zero at the cathode. It is only the *time average* field, however, that is zero at any point on the cathode. The *instantaneous* field at any point may vary in a random manner between positive and negative values. Immediately after one or more electrons have entered some point of the anode, the net field at a corresponding

Operation

- A.C. input is applied the plate 'P' becomes positive and negative alternately.
- For the positive half cycle of input, the plate is positive with respect of cathode. So that diode conducts and plate current flows through the tube load R_L and secondary. So output occurs across load. R_L as shown in fig. (ii).

Important Points

- During – ve half cycle of A.C. input, →Plate is negative with respect to cathode. So the diode does not conduct, and no voltage appears across output.
- For half wave rectifier; (I_0 is peak value of current)
  - → Average value of current $I_{D.C.} = I_0/\pi$
  - → Root mean square value of current $I_{rms} = I_0/2$
  - → Maximum efficiency $\eta_{max} = 40{\cdot}6\%$
  - → Ripple factor $r = 1{\cdot}21$

(B) **Full wave rectifier**—It converts full A.C. into D.C. In this rectifier two diodes are used which conduct alternately. The output is obtained across the load resistance R_L. Here in first half cycle of A.C., plate of first diode remains positive and plate of second diode remains negative. Hence, the first diode conducts and the second does not. In second half cycle of A.C., plate of the first diode becomes negative and that of second diode becomes

Rectifier

Rectifier is a device which converts an A.C. into a D.C. The process is called **Rectification**. Rectifiers are of two types :

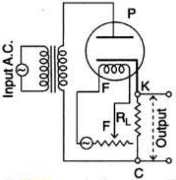
1. **Half wave rectifier**—Which conducts only during + ve half cycle of input A.C.

2. **Full wave rectifier**—Which conducts during full cycle of input A.C.

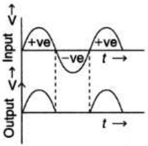
(A) **Half wave rectifier** (in half wave rectifier only one diode valve is used)

Circuit

- The input A.C. voltage to be rectified is applied to the primary of a transformer.
- The secondary of transformer is connected in series with load R_L between plate and cathode of diode (as shown in fig.).



(i) Diode as a half-wave rectifier



(ii) Input and output waveforms

point of the cathode may be positive, causing one or more electrons to move away from the cathode. These electrons produce a retarding field behind them which prevents the departure of more electrons from that point until the entrance of other electrons into the anode again results in an accelerating field. Many electrons are entering and leaving the space at any instant, so that the field fluctuations are rapid and haphazard.

2-10. Child's Law.—The foregoing descriptive explanation shows that, if an ample supply of electrons is available at the cathode, the anode current in a diode varies with the voltage applied between the anode and cathode. A mathematical analysis of this phenomenon was first made by Child.[1] The equation relating the anode current and voltage is called *Child's law*. The general derivation for electrodes of any size and shape is too difficult to yield a useful equation, and so only the relatively simple cases such as those applying to plane parallel electrodes of large area and to long concentric cylinders are ordinarily considered. In deriving Child's law for plane parallel electrodes the following assumptions are made:

1. The cathode temperature is high enough at all points so that more electrons are emitted than are drawn to the anode; *i.e.*, the current is limited by space charge.
2. The cathode and anode are parallel plates whose area is large as compared to their spacing; *i.e.*, the electrostatic field is uniform over the surface of any plane parallel to the electrodes.
3. The surfaces of the anode and cathode are equipotential surfaces.
4. The space between the cathode and the anode is sufficiently free of gas so that electrons do not lose energy by collision with gas molecules in moving from the cathode to the anode.
5. Emitted electrons have zero initial velocity after emission.

Under these assumptions the following three equations may be written:

$$\frac{\partial^2 V}{\partial x^2} = 4\pi\rho \qquad (2\text{-}2)$$

$$\varepsilon V = \tfrac{1}{2} m_e v^2 \qquad (2\text{-}3)$$

$$\rho v A = i_b \qquad (2\text{-}4)$$

in which V is the potential, relative to the cathode, at a distance x from the cathode; ρ is the density of electron space charge at a

[1] CHILD, C. D., *Phys. Rev.*, **32**, 498 (1911).

distance x from the cathode; $\mathcal{E}$ and m_e are the charge and mass, respectively, of an electron; v is the velocity dx/dt of an electron at a distance x from the cathode; i_b is the anode current; and A is the area of the electrodes.

Equation (2-2) combines in symbolic form the definitions of potential difference and electric field. It is a special form of Poisson's equation, one of the most important fundamental laws of electrostatics, and may be derived directly from Gauss's law[1] (see Sec. 1-10). Equation (2-3) states that the energy gained by an electron in moving from the cathode to a distance x from the cathode under the influence of the electric field appears entirely in the form of kinetic energy. Equation (2-4) is a symbolic formulation of the definition of the magnitude of an electric current as the rate of flow of charge.

In the solution of the simultaneous differential Eqs. (2-2), (2-3), and (2-4), the following boundary conditions must be applied: At the cathode, the potential V, the average electric field $\partial V/\partial x$, and the velocity v are zero. At the anode, where x is equal to the cathode-to-anode spacing d, the potential is equal to e_b, the applied anode voltage. Solution of the equations and substitution of numerical values of $\mathcal{E}$ and m_e give the following equation for the anode current of a diode:[2]

$$i_b = 2.34 \times 10^{-6} \frac{A e_b^{3/2}}{d^2} \quad \text{amp} \qquad (2\text{-}5)$$

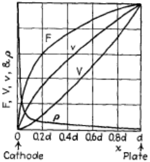


FIG. 2-9.—Variation of field strength F, potential V, electron velocity v, and space-charge density ρ with distance x from plane cathode. Zero initial velocity. Arbitrary units.

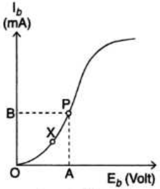
By combining Eq. (2-5) with Eqs. (2-2), (2-3), and (2-4), theoretical expressions may be derived for density of space charge, electron velocity, electric field strength, and potential as functions of distance from the cathode. Curves derived from these are shown in Fig. 2-9.

Child's law for concentric cylinders whose length is large as compared to their spacing is

[1] PAGE, L., and ADAMS, N. I., "Principles of Electricity," p. 83, D. Van Nostrand Company, Inc., New York, 1931.

[2] PAGE and ADAMS, *op. cit.*, p. 297.

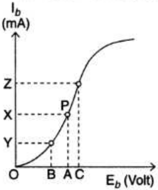
as D.C. plate resistance. The D.C. plate resistance R_p is given by



$$R_p = \frac{OA}{OB}$$

Note : Since plate characteristic curve is not a straight line—Therefore, D.C. plate resistance is variable. Hence, D.C. plate resistance may be calculated at the actual operating point.

(ii) **A. C. plate resistance**—The ratio of a small change in plate voltage across a diode to the resulting change in plate current is known as A.C. plate resistance.



$$r_p = \frac{\Delta V}{\Delta I}$$

Note : The A.C. plate resistance at operating point P can be found by considering small equal changes of plate voltage on either side of the operating point (*i.e.*, AB = A.C.)

$$\text{Change in plate voltage} = BC$$

$$\text{Change in plate current} = YZ$$

$$\therefore \text{A.C. plate resistance at } p,\ r_p = \frac{BC}{YZ}$$

2. At $V_p = V_1$, almost all the electrons constituting space charge are collected by plate and space charge is eliminated. At this point rate of collection of electrons reaches its maximum value and it equals the rate of emission of electrons by cathode. Therefore, if plate voltage is further increased plate current becomes constant.
3. The only way to increase the plate current is to increase the rate of emission, *i.e.*, to increase the temperature of cathode. Since the plate current, in this region, may be limited by temperature of cathode, this is called **temperature limited region**. In this region plate current is independent of plate voltage and varies with temperature T of cathode as

$$I = cT^2 e^{-b/T} \qquad \text{...(ii)}$$

where c and b are constant for cathode.

Equation (ii) is simplified form of Richardson equation for this case.

Plate resistance of diode—The plate current (I_p) varies as the plate voltage (V_p) is changed, therefore, a diode offers internal resistance which is known as its plate resistance.

Note : Mainly negative space charge is responsible for the plate resistance of diode. As it is a non-ohmic resistance its value is not constant and it differs at different operating points.

Types of Plate Resistance

(i) **D.C. plate resistance**—The ratio of total D.C. plate voltage across diode to the resulting current is known

$$i_b = 14.68 \times 10^{-6} \frac{he_b^{3/2}}{br} \quad \text{amp} \qquad (2\text{-}6)$$

in which r is the radius of the anode, h is the length of the electrodes, and b is a factor whose value depends upon the ratio of the radius of the anode to that of the cathode. b has the approximate value $\frac{1}{4}$ for a ratio 2, $\frac{1}{2}$ for a ratio 3, and 0.9 for a ratio 8. If the plate diameter is large as compared to that of the cathode, Eq. (2-6) reduces to the approximate form

$$i_b = 14.7 \times 10^{-6} \frac{he_b^{3/2}}{r} \quad \text{amp} \qquad (2\text{-}7)$$

Equations (2-5), (2-6), and (2-7) show the importance of close spacing between cathode and anode if large currents are desired at small anode voltages.

2-11. Deviations from Child's Law Observed in Practical Diodes.—Deviations from Child's law result from the failure of practical diodes to satisfy the assumptions made in its derivation. Since the temperature of the cathode is fixed by considerations of emission efficiency and life, there is always a saturation voltage above which the current is not limited by space charge but by filament emission. If other assumptions were satisfied, the

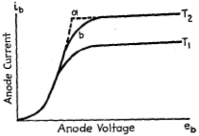


FIG. 2-10.—Curves of anode current *vs.* anode voltage at two values of emitter temperature.

saturation voltage would be quite definite and the current-voltage curve would be as shown by the dotted lines of Fig. 2-10. Because of variations in temperature, electron affinity, and field strength over the cathode surface, the anode voltage at which voltage saturation takes place is not the same for all points of the cathode. The curve of anode current *vs.* anode voltage therefore bends over gradually, as shown by the full line of Fig. 2-10. Above saturation the current is not entirely constant but continues to rise somewhat with anode voltage. This is explained by reduction of electron affinity with increase of external field (see Sec. 1-12), and lack of homogeneity of the surface of the emitter. The effect is particularly noticeable with oxide-coated cathodes.

The assumptions of uniform field and equipotential cathode are satisfied fairly closely in heater-type diodes with cylindrical plates. The voltage drop in filamentary cathodes may be shown to change Child's $\frac{3}{2}$-power law into a $\frac{5}{2}$-power law at anode voltages relative to the negative end of the filament that are less than the voltage of the positive end of the filament. This tends to make the lower part of the i_b-e_b curve steeper. The exact effect upon the curve of failure to satisfy the assumption of uniform field is complicated and impossible to predict completely.

2-12. Effect of Initial Velocities of Emitted Electrons.—Modified forms of Child's law which take into consideration the initial velocities of emitted electrons have been derived by Schottky, Langmuir, and others.[1] For the purpose of this book, a qualitative explanation of the effect of initial velocities is sufficient. Let it first be supposed that the electrons emerge with zero velocity. Under equilibrium conditions the space current and the space-charge density assume such values that the average field at the cathode is zero. The field and potential distributions in the interelectrode space are as shown in Fig. 2-9. Now let the emitted electrons suddenly have initial velocities that, for the sake of simplicity, are assumed to be the same for all electrons. Electrons that, without initial velocity, would have reentered the cathode now move toward the anode in spite of the fact that the average field is zero. As a result, the current and the space-charge density increase. The retarding field of the space charge now exceeds the accelerating field of the anode, giving a net retarding field at the cathode surface which slows up the electrons in the vicinity of the cathode. Equilibrium results when the retarding field in the vicinity of the cathode is sufficiently high so that the electrons are brought to rest in a plane a short distance s from the cathode. The average field in

[1] SCHOTTKY, W., *Physik. Z.*, **15**, 526 (1914); *Ann. Physik*, **44**, 1011 (1914). LANGMUIR, I., *Phys. Rev.*, **21**, 419 (1923). DAVISSON, C., *Phys. Rev.*, **25**, 808 (1925).

We note from fig. (i) that curves coincide at low voltage (in space charge limited region) but saturation current increases as shown by portion CD of characteristics.

(2) **Low voltage characteristics**—The plate current is practically zero at zero plate voltage (however, plate current is not exactly zero). If we measure plate current using a micro-ampere plate current of the order of few micro-ampere occurs. This is due to "the fact that even at zero plate voltage a few electrons may have sufficient K.E. to reach the plate and constitute a plate current of few micro-ampere." From the fig. (ii) the plate current becomes exactly zero at a particular negative value V_C of plate voltage, called **cut-off voltage.** The max. kinetic energy of emitted electron is related to V_C as :

$$K_{max} = e V_C$$

Important Points

1. If we increase plate voltage from zero volt to a value V_1 in steps, more and more electrons are attracted from space charge to plate (though at the same time same no. of electrons are emitted from cathode so that space charge is maintained) so plate current increases. As the plate current is limited by space charge, this region of curve is called **space charge limited region**. In this region, plate current is related to plate voltage by equation.

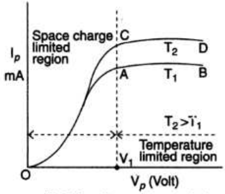
$$I_p = K . V_p^{3/2} \qquad ...(i)$$

where K is a constant.

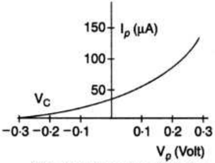
Equation (i) is known as **Child-Langmuir's law.**

V-I characteristics of Diode

(1) **High voltage characteristics**—Fig. (i) shows high voltage plate characteristics when plate current is measured in (mA). Keeping temperature of cathode constant, say (T_1) (*i.e.* filament current constant) when plate voltage increased from zero volt in steps and corresponding value of plate current i_p measured in m.A. the variation occurs as shown in curve OAB. If the cathode temperature is increased from T_1 to T_2.



(i) High voltage characteristics



(ii) Low voltage characteristics

Fig. : V-I characteristics of diode.

this plane is zero, but instantaneous fluctuations allow just enough electrons to pass to give the required anode current. The behavior is similar to that which would obtain if the initial velocity were zero and the cathode were moved toward the anode by the distance s. Because of the random distribution of electron velocities the phenomenon is actually more complicated than this simplified picture indicates. The simple theory shows, however, that the effect of initial velocities is to increase the anode current corresponding to any anode voltage and is therefore equivalent to that of a small increase of anode voltage. Because the electrons emerge with velocities of the order of a volt or less, the effect is appreciable only for low anode voltages. The field and potential distributions throughout the interelectrode space are plotted in Fig. 2-11. That the potential must pass through a minimum where the field is zero follows from the fact that the field at any point may be expressed as the space derivative of the potential at that point.

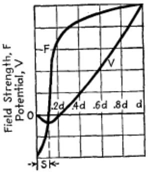


FIG. 2-11.—Variation of field strength and potential with distance from cathode for plane parallel electrodes of separation d. Initial velocities of emitted electrons considered.

The lower part of the i_b-e_b curve of Fig. 2-10 is raised slightly as the result of initial velocities of emitted electrons, and a small negative voltage must be applied in order to reduce the anode current to zero. Theoretical equations relating anode current and voltage at negative anode voltages have been derived by Schottky[1] and Davisson.[2] Because of their complicated form and because of failure to satisfy in practice the assumptions made in their derivation, these are seldom of great practical value. At negative anode voltages that are high enough to reduce the anode current to the order of 50 μa or less, the anode current of diodes with unipotential cathodes follows closely the empirical relation

$$i_b = k_1\epsilon^{k_2e_b} \qquad (2\text{-}8)$$

in which k_1 and k_2 are constants for a given tube. The current

[1] SCHOTTKY, *loc. cit.*; LANGMUIR, *loc. cit.*
[2] DAVISSON, *loc. cit.*

departs materially from this exponential law as the negative anode voltage is reduced in the vicinity of zero voltage, particularly at high cathode temperatures. Experimental curves corresponding to Eq. (2-8) were first obtained by Germer.[1]

Unless the plate of a highly evacuated diode becomes hot enough to emit electrons, increase of negative anode voltage beyond the value that reduces the current to zero has no further effect upon the anode current. The fact that anode current flows in one direction only is employed in the application of diodes to detection and to power rectification, which will be discussed in Chaps. 7 and 11.

2-13. Relation of Richardson's and Child's Laws.—It should be noted that Richardson's equation and Child's law apply to two different conditions of operation of two-element tubes. Richardson's equation holds only under voltage saturation, whereas Child's law applies only under temperature saturation. In most applications, vacuum tubes are used in such a manner that temperature saturation prevails.

2-14. Shot Effect.—The random motion of electrons causes rapid variations of the number of electrons that pass from the cathode to the anode in unit time, and thus produces fluctuations of anode current. This phenomenon, which may be readily detected by the use of sufficient amplification, is called the *shot effect*. It is one of the factors that limit amplification by vacuum tubes (see Sec. 6-15).

Heating of the Plate.—The kinetic energy acquired by electrons in moving from the cathode to the plate is converted into heat when the electrons strike the plate. The average current that a vacuum tube can pass is limited by the temperature of the plate at which absorbed gas is driven out of the plate or electron emission takes place from the plate. The power that is converted into heat at the plate is equal to the time integral of the product of the plate current and plate voltage. Radiation of heat from the plate is increased by blackening its outer surface.

2-15. Classification of Tubes.—Electron tubes may be classified in a number of ways. These classifications include those based upon the process involved in the emission of electrons from the cathode, the degree of evacuation, the number of elec-

[1] GERMER, L. H., *Phys. Rev.*, **25**, 795 (1925).

plate current. These electrons flow through the external circuit and finally return to the cathode, thus making up the supply of electrons lost by emission. On increasing plate potential more electron will gain sufficient kinetic energy so as to reach anode, hence the plate current increases.

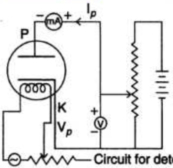
Important Points to Note

- The current flows in the diode only when plate is made positive relative to cathode.
- No current can flow when plate is negative relative to cathode.
- Within a diode electrons can flow only from cathode to plate.
- Due to unidirectional conduction property the diode acts like a valve.
- The diode automatically starts conduction when the plate is positive or stops conduction when the plate is negative (due this property) the diode may act as a rectifier, converting A.C. into D.C.)

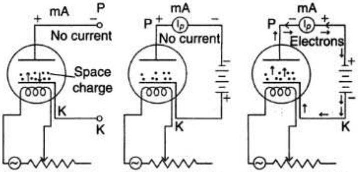
Characteristics of Diode

Characteristics of vacuum diode can be best studied by finding the relation between plate voltage and plate current for a given cathode temperature.

The circuit for determining the plate characteristic of an indirectly heated vacuum diode is shown in fig.



Circuit for determining plate characteristics of diode



(i) Plate is open (ii) Plate is given –ve potential (iii) Plate is given +ve potential

(1) **Anode (plate) at zero potential relative to cathode**—This situation is shown in fig. (i)—The emitted electrons do not have sufficient kinetic energy so as to reach the anode. However, a few electrons may reach the anode on account of their kinetic energy, constituting negligible current. The emitted electrons accumulate near the cathode and form a cloud of electrons. This is known as space charge. At a certain stage the number of electrons forming the space charge becomes constant for a given operating temperature. This space charge becomes a source of electrons that can be attracted to the plate, if it is at a positive potential.

(2) **Anode (plate) at negative potential relative to cathode**—This situation is shown in fig. (ii). The emitted electrons are repelled back due to retarding potential of anode. For a particular negative potential of anode plate current may be zero.

(3) **Anode (plate) at positive potential relative to cathode**—This situation is shown in fig. (iii). The electrons constituting the space charge are attracted to the plate. This flow of electrons from cathode to plate is known as

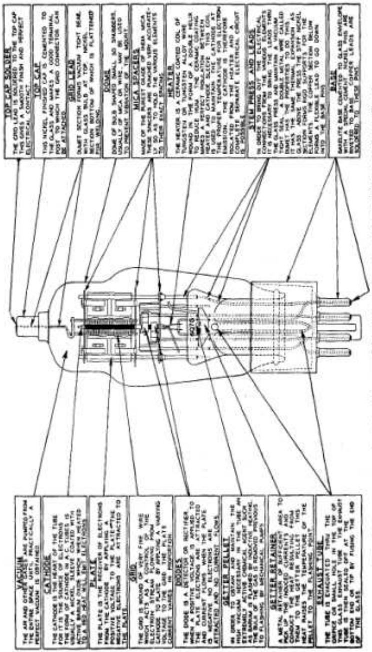


FIG. 2-12.—Structure of a typical glass receiving tube. (*Courtesy of Ken-rad Tube and Lamp Corp.*)

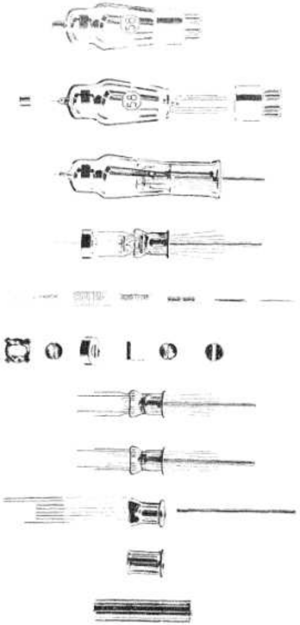


FIG. 2-13.—Assembly of a typical glass receiving tube. (Courtesy of Radio Corporation of America.)

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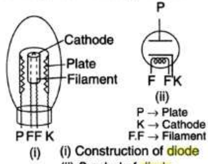
Vacuum Diode or Diode Valve

A vacuum diode consists of two electrodes : a cathode; and an anode enclosed in an evacuated glass tube. Its operation is based upon thermionic emission, it is also called thermionic diode.

Anode (or plate)—The anode is a hollow cylinder made of Ni or molybdenum and surrounds the cathode.

Cathode—A cathode may be directly heated or indirectly heated type. Usually an indirectly heated cathode is provided (except in high power application).

As shown in fig. (i) an indirectly heated cathode is in the form of nickel cylinder coated with oxides of barium or strontium. Inside the cathode, a heater filament of tungsten is inserted.



(i) Construction of diode
(ii) Symbol of diode

Fig. (ii) shows it symbol :

Operation of diode—When electric current is passed through the diode it emits a large number of electrons. These emitted electrons may be accelerated or retarded by applying positive or negative potential to anode relative to cathode.

the mutual conductance to decrease, which means that the amplification obtainable from the tube also decreases since amplification is proportional to mutual conductance, other things being equal. On the other hand, the plate resistance increases with increasing negative grid bias. As a check on the accuracy of measurement, the three curves should satisfy the relationship

$$g_m = \frac{\mu}{r_p}$$

within reasonable limits of accuracy, for any given value of grid bias.

If published average curves for the type of tube measured are available, it will be of interest to compare them to the curves determined experimentally. Exact duplication of the published curves is not to be expected, of course, because of slight variations in manufacture.

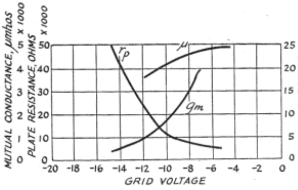


Fig 9.

trodes, and the type of application. Included in the first classification are the thermionic tube and the phototube. A *thermionic tube* is an electron tube in which the electron or ion emission is

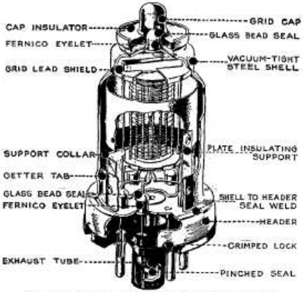


FIG. 2-14.—Structure of typical metal receiving tube.

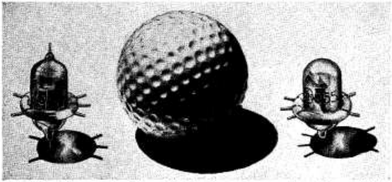


FIG. 2-15.—Size of typical "acorn" tubes shown in comparison with a golf ball. (*Courtesy of Radio Corporation of America.*)

produced by the heating of an electrode. A *phototube* is an electron tube in which electron emission is produced directly by radiation falling upon an electrode. According to degree of evacuation, electron tubes are classified as high-vacuum tubes and gas- or vapor-filled tubes A *high-vacuum tube* (*vacuum tube* or *pliotron*) is an electron tube evacuated to such a degree that its electrical characteristics are essentially unaffected by gaseous ionization. A *gas-filled* or *vapor-filled tube* (*gas tube*) is an electron tube in which the pressure of the gas or vapor is such as to affect appreciably the electrical characteristics of the tube. According to the number of electrodes, tubes are classified as *diodes, triodes, pentodes,* etc. For convenience or economy or for reduction of space or weight, two or more sets of elements may be enclosed in a single envelope. Thus, there are duplex (double) triodes, duplex-diode pentodes, triode pentodes, etc. The diverse classification of electron tubes according to application will be made in later chapters.

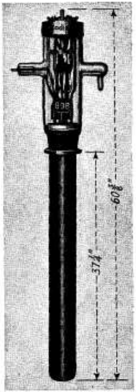


FIG. 2-16.—100-kw water-cooled transmitting tube. (*Courtesy of Radio Corporation of America.*)

2-16. Construction of Tubes.—Tubes are made with both glass and metal envelopes.[1] The principal advantages of metal tubes lie in their greater mechanical strength and in the fact that the electrodes are permanently and completely shielded without the use of an external shield. Furthermore, they do not require on the inside of the envelope the conducting coating that must be used in glass tubes to prevent the wall from acquiring a positive charge as the result of secondary emission caused by the impact of electrons that pass around the plate. A disadvantage of metal tubes is that the shells become so hot in operation that they cannot be conveniently handled. This is of importance in the routine factory testing of radio receivers. Another minor disadvantage is the impossibility of determining visually whether the heater is in operation. Glass tubes appear to be somewhat more reliable. In rectifiers, particularly, metal

[1] PIKE, O. W., and METCALF, G. F., *Electronics*, October, 1934, p. 312. See also *Electronics*, September, 1935, p. 31.

The values of amplification factor, µ, plate resistance, rp, and mutual conductance, gm, can be measured from these three sets of curves. The mutual conductance, ΔIpΔEg can be found from the curves of Fig. 6 since these curves show the relationship between grid voltage and plate current. The plate resistance, ΔIp/ΔEp, can be measured from the curves of Fig.: 7, which relate plate current to plate voltage for various values of grid bias, while the amplification factor ΔIpΔEg, can be taken from the curves of Fig. 8. The method of making these measurements is described in the introduction to this installment. Since these "constants" are a function of three variables a large number of graphs would be required to give their behavior even partially completely, but one special case is shown in Fig. 9. This graph shows the variation in µ, rp and gm as a function of grid bias when the plate voltage is held constant at 250 volts, the normal rated operating voltage for the tube, and is a plot of values measured at 250-volt points on each of the three sets of curves in Figs. 6, 7 and 8. It is plain that the amplification factor changes relatively little compared to the changes in the other two quantities. Increasing negative grid bias causes

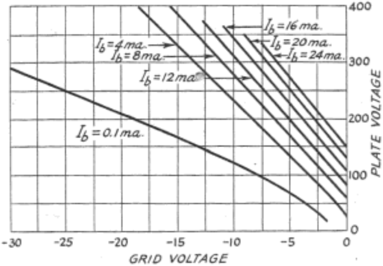


Fig. 8

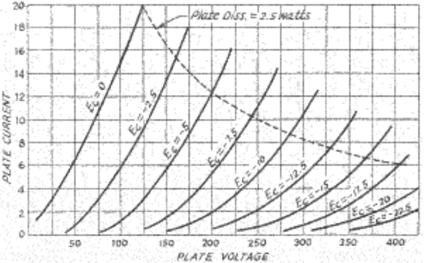


Fig. 7

The "plate family," shown plotted from experimental data in Fig. 7, is obtained by holding the grid bias constant at selected values and measuring the plate current as the plate voltage is varied. These curves show the same general tendency to bend when the plate current is near cut-off, and to straighten out at higher values of plate current. The plate family is frequently more useful than the set of grid voltage-plate current curves represented by Fig. 6.

When the remaining quantity, plate current, is held constant while the grid voltage is varied (the plate voltage being adjusted for each value of grid bias to give the selected value of plate current) the set of curves shown in Fig. 8 results, again plotted from experimental data on a 6J5. These "constant current" curves show the relative effect of grid voltage and plate voltage on plate current. The curves are nearly straight lines for all except very small values of plate current, showing that the amplification factor is practically constant for a given plate-current value regardless of the plate and grid voltages. The fact that, with the exception of the curve for a plate current of 0.1 milliampere, the curves are very nearly parallel indicates that the amplification factor also is nearly independent of the plate current so long as the latter is not near the cut-off point.

tubes are likely to give difficulty as the result of short circuits. Figures 2-12 and 2-13 show the construction of a glass receiving tube; Figs. 2-14 and 3-11*b* show typical metal receiving tubes.

The great range in size of vacuum tubes is illustrated by Figs. 2-15 and 2-16. Figure 2-15 shows a typical *acorn* tube, developed for use at very high frequencies, at which it is essential

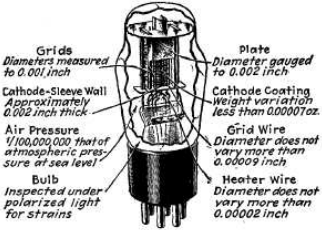


FIG. 2-17.—Materials used in typical radio receiving tubes. The complex nature of the structure of the modern vacuum tube, and of the manufacturing processes, is well illustrated by a consideration of the materials that are used.

Gases.—Argon, carbon dioxide, chlorine, helium, hydrogen, illuminating gas, neon, nitrogen, and oxygen.

Metals and Compounds.—Alumina, aluminum, ammonium chloride, arsenic trioxide, barium, barium carbonate, barium nitrate, borax, boron, cesium, calcium, calcium aluminum fluoride, calcium carbonate, calcium oxide, carbon, chromium, cobalt, cobalt oxide, copper, iridium, iron, lead, lead acetate, lead oxide, magnesia, magnesium, mercury, misch metal, molybdenum, monel, nickel, phosphorus, platinum, potassium, potassium carbonate, silica, silicon, silver, silver oxide, sodium, sodium carbonate, sodium nitrate, tantalum, thorium, thorium nitrate, tin, titanium, tungsten, zinc, zinc chloride, and zinc oxide.

Accessories.—Bakelite, ethyl alcohol, glass, glycerine, isolantite, lava, malachite green, marble dust, mica, nigrosine, petroleum jelly, porcelain, rosin, shellac, synthetic resin, and wood fiber.

to keep lead capacitance and inductance as small as possible.[1] No base is used on the acorn type of tube, connections being made directly to the electrode leads. Figure 2-16 shows a 100-kw water-cooled transmitting tube of a type that is used in large broadcasting stations.

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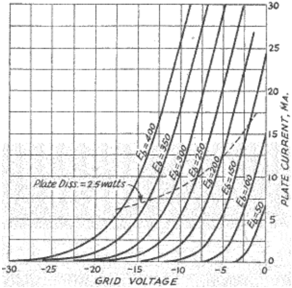


Fig. 6

enough points being taken at each plate voltage to permit smooth curves to be drawn. Notice that for each value of plate voltage the curve bends at the higher values of negative grid voltage (as the plate current decreases toward the cutoff point) but that the curvature decreases as the grid bias becomes less negative. The curves eventually straighten out and become practically parallel, and the distances between the 50-volt intervals also approach equality. The dashed line shows the value of plate current at which the plate dissipation (plate voltage multiplied by plate current) is equal to the maximum rated value for the tube; above this line the plate dissipation is exceeded.

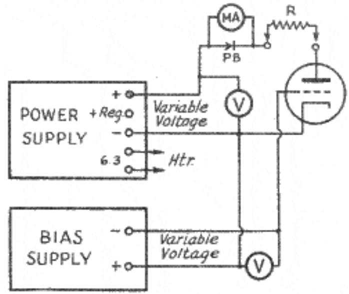


Fig. 5

The resistor R shown in Fig. 5 is not needed in this experiment, so the push-button may be connected directly to the plate.

Procedure: The object of the experiment is to determine the relationship between plate voltage, plate current and grid voltage of a small triode. One quantity is held constant throughout a run, the second is varied, and corresponding measurements of the third are made. A receiving triode such as the 6J5 is suitable. Three sets of characteristics can be taken; the first, with the plate voltage held fixed while the behavior of plate current with varying grid voltage is observed, is called the "grid voltage plate current" characteristic. When a series of such data is taken with several fixed values of plate voltage, a "family" of curves results. A typical grid-voltage plate-current family taken in this way on a 6J5 is shown in Fig. 6. The plate voltage was set at 50- volt intervals from 50 to 400 volts (the maximum output voltage of the power supply described in August QST),

Lecture 19 ANALYSIS OF RECTIFIER OPERATION
0. H. Schade

INTRODUCTION

The design of diodes for rectification of a-power requires unusual care even though their design is simple from the standpoint of the number of electrodes involved. The cathode must be capable of supplying the average current and peak current which will be encountered in ser-vice. The plate must operate at a safe temperature, which in turn depends on plate dissipation, the physical dimensions of the plate, and the thermionic and thermal emissivity of the plate material. Another factor to be considered is the purveyance of the diode, i.e., the steepness of its voltage-current characteristic. Purveyance affects both cathode— and plate-design because it controls current density and voltage gradient at the effective surfaces of both for a given cathode area. Then, too, there is the requirement for adequate insulation. Perveance and insulation requirements depend on the type of service in which the diode is to be used.
It is apparent that an analysis of diode-operating conditions in rectifier circuits is essential in order to arrive at optimum design specifications in each particular case, because the required data bear no simple relationship to the values of rectified current and voltage.

PRINCIPLES OF RECTIFICATION

1. General

Rectification is a process of synchronized switching. The basic rectifier circuit consists of one synchronized switch in series with a single-phase source of single frequency and a resistance load. The switch connection between load terminals and source is closed when source and load terminals have the same polarity, and is open during the time of opposite polarity. The load current consists of half-wave pulses. This simple circuit is unsuitable for most practical purposes, because it does not furnish a smooth load current.

The current may be smoothed by two methods:(a) by increasing the number of phases, and (b)by inserting reactive elements into the circuit. The phase number is limited to two for radio receivers. The circuit analysis which follows later en will treat single- and double-phase rectifier circuits with reactive circuit elements.
Switching in reactive circuits gives rise to “transients." Current and voltage can, there-fore, not be computed according to steady-state methods.
The diode functions as a self-timing electronic switch. It closes the circuit when the plate becomes positive with respect to cathode and opens the circuit at the instant when the plate current becomes zero.
The diode has an internal resistance which is a function of current. When analyzing rectifier circuits, it is convenient to treat the internal resistance of the diode rectifier as an element, separated from the "switch action" of the diode. Fig. 1 illustrates the three circuit elements so obtained. The diode characteristic is the geometric sum of these characteristics. The resistance r^ is effective only when the switch is closed, i.e., during the conduction period of the diode. The effective diode resistance must, therefore, be measured or evaluated

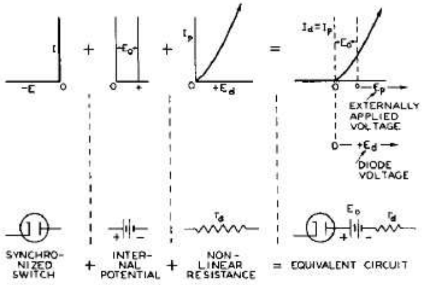


Fig 1

small fraction of a milliampere - it can be neglected in most applications of the tube. However, in flowing through an external load resistance of high value a volt or two may be developed across the load, which may need to be taken into account in some cases.

Triode Static Characteristics

Experiment 22

Apparatus: The set-up for this experiment is shown in Fig. 5. Insofar as the plate circuit of the triode is concerned. the arrangement is practically the same as that used for diode measurements, :Fig. 3, except that it is possible to measure plate voltage with the test instrument rather than the v.t. voltmeter. This is because larger plate voltage steps may be used so that a high range (500 volts or the nearest provided on the test instrument), which will have a resistance of a half megohm or so, will give sufficient accuracy for all measurement. The bias supply is incorporated in the

set-up to provide variable grid bias, and its voltage output also may be measured by the test instrument on the condition that the voltmeter resistance is 25,000 ohms or so (25-volt scale). Be sure that the positive output terminal of the bias supply is connected to the grounded side of the 115-volt line, using the lamp provided for checking as described in July QST. In using a single instrument in place of the three indicated, the push-button should be closed each time the plate voltage is measured so that the voltage will be that existing when plate current flows.

the behavior of the tube when an alternating voltage is applied is of more interest, in which case the a.c, plate resistance, or resistance effective to small changes in applied voltage, is important. The value of this plate resistance is found as described in the introduction to this installment.

When a load resistance is inserted in the plate circuit the linearity of the circuit consisting of the resistance and the tube is better than that of the tube alone. This improvement, which increases as the load resistance is increased, is because the load resistor tends to reduce the effect of variations in the resistance of the tube. For example, if the resistance of the tube varies between 1000 and 3000 ohms with a

certain range of applied voltage the resistance change is 2000 ohms, or an increase of 200%, using the smaller number as a base, If a 10,000-ohm resistor is connected in series, the minimum resistance becomes 11,000 ohms and the maximum resistance 13,000 ohms, so that the increase in resistance is now only 2000/11,000, or 18%. With 100,000 ohms in series, the increase is from 101,000 to 103,000 ohms, so that the percentage increase is now 2%. In the curves of Fig. 3 the addition of the load resistance makes all the points fall on a line which is practically straight except at the low voltage end where the tube resistance has its highest value. The higher the load resistance the less marked does this slight curvature become.

In taking data it will be observed that a small current flows in the plate circuit even at zero plate voltage.

This current is the result of the fact that some electrons are emitted from the cathode with sufficient velocity to reach the plate even though there is no positive charge on the plate to attract them. For complete cut-off of plate current

it would be necessary to make the plate a volt or two negative with respect to the cathode, thus repelling these high energy electrons from the plate. Since the current in any case is very small - a very

within conduction-time limits. Consider a switch in series with a fixed resistance and any number of other circuit elements connected to a battery of fixed voltage. The d-c current and rms current which flow in this circuit will depend on the time intervals during which the switch is closed and open; the resistance value is not obtainable from these current values and the battery voltage. The correct value is obtained only when the current and voltage drop in the resistance are measured during the time angle φ (Fig. 2) when the switch is closed.
The method of analysis of rectifier circuits to be discussed in this lecture is based on the principle that the non-linear effective resistance of the diode may be replaced analytically by an equivalent fixed resistance which will give a diode current equal to that obtained with the actual non-linear diode resistance. The correct value to be used for the equivalent fixed resistance depends upon whether we are analyzing for peak diode current, average diode current, or rms diode current. As will be seen later, the relations among these three equivalent resistances depend upon the circuit under consideration.

2. Definitions of Resistance Values
The instantaneous resistance (r^) of a diode is the ratio of the instantaneous plate voltage e^, to the instantaneous plate current, ip, at any point on the characteristic measured from the operating point (see Fig. 1). It is expressed by the equation

$$r_d = \frac{e_d}{i_p}$$

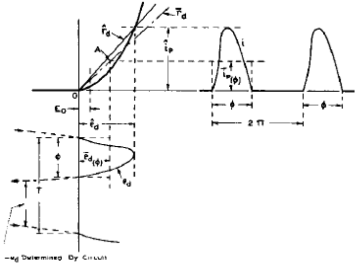


Fig 2

The operating point (0) of a diode is a fixed-point on the characteristic, marked by beginning and end of the conduction time. It is, there-fore, the cut-off point Id = 0 and Ed = 0, as shown in Fig. 1. The operating point is independent of the waveform and of the conduction time φ (see Fig.2).

The peak resistance (¾) is a specific value of the instantaneous resistance and is defined as

$$\hat{r}_d = \frac{\hat{e}_d}{\hat{i}_p} \quad \text{(See Fig.2)}$$

Peak voltage e<j and peak current ip are measured from the operating point 0.
The equivalent average resistance (rd) is de-fined on the basis of circuit performance as a resistance value determining the magnitude of the average current in the circuit. The value r^ is, therefore, the ratio of the average voltage drop β(}(φ) in the diode during

necessary to make provision for closing the plate circuit of the v.t.v.m. when the meter is being used elsewhere.

The observed data should be plotted in the fashion shown in Fig. 4, which gives characteristic curves taken on a 6H6. With no load the current is quite high, reaching 10 milliamperes with about 7.5 volts applied. Other types of tubes may give considerably different plate current values without load, but should approximate the load curves given since the current which flows at a given voltage is principally determined by the load resistance rather than the tube. As is to be expected, the current decreases, at a given applied voltage, as the load resistance is increased.

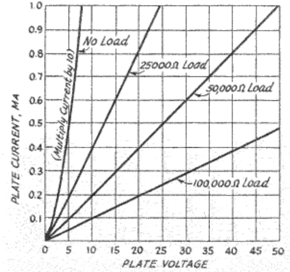


Fig 4

If the no-load curve is inspected carefully, it will be observed that it is not a straight line, particularly near the low-voltage end. The lamp in Exp. 10 was another example of a non-linear circuit, although for a different reason. In the present case, the nonlinearity arises from the fact that the number of electrons drawn to the plate is not strictly proportional to the voltage applied between plate and cathode, The d.c. resistance of the diode at any voltage is equal to that voltage divided by the current which it forces through the tube. In practice

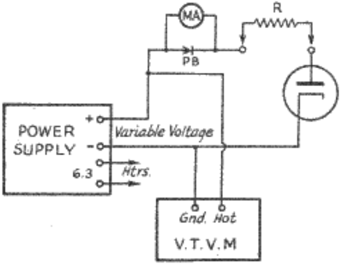


Fig 3.

Procedure: The object of the experiment is to plot characteristic curves, plate voltage vs. plate current for the tube alone (static characteristic) and with various values of load resistance in series with the plate circuit (dynamic characteristics). Starting at zero plate voltage, increase the plate voltage in small steps, taking plate current readings at each voltage step. With no load resistor in the circuit, take readings at intervals of voltage which will give current intervals of about 1 milliampere so that enough points will be secured to give a smooth curve when the points are plotted. In the case of the 6H6 tube, using one plate and cathode only, one-volt intervals are suitable. Proceed similarly when the load resistance is inserted in the circuit; in this case larger voltage intervals (5-volt steps, for instance) can be used

In using the single test set for all measurements. the pushbutton should be closed while the voltage measurement is being made so that the voltage can be adjusted to the proper value with plate current flowing. If the plate circuit is not closed at the time the voltage is adjusted, the voltage will drop when the milliammeter is connected in the plate circuit of the tube to measure plate current. It is not

conduction time to the average current ip(<p) during conduction time, or

$$\bar{r}_d = \frac{\bar{e}_{d(\varphi)}}{\bar{i}_{p(\varphi)}}$$

The curved diode characteristic is thus replaced by an equivalent linear characteristic having lie slope ?d and intersecting the average point A, as shown in Fig. 2. The coordinates ed(q>) and ip (φ) of the average point depend on the shape of voltage and current within the time angle φ.

The analysis of rectifier circuits shows that the shape of the current pulse in actual circuits varies considerably between different circuit types. The equivalent rms resistance (|r^I) is de-fined as the resistance in which the power loss Pd is equal to the plate dissipation of the diode when the same value of rms current II^I flows in the resistance as in the diode circuit. It is expressed by the equation:

$$|r_d| = \frac{P_d}{|I_d|^2}$$

3. Measurement of Equivalent Diode Resistances The equivalent resistance values of diodes can be measured by direct substitution under actual operating conditions. The circuit arrangement is shown in Fig. 3. Because the diode under test must be replaced as a whole by an adjustable resistance of known value, a second switch (a mercury-vapor diode identified in the figure as the ideal diode) with negligible resistance must be inserted in order to preserve the switch-action in the circuit.

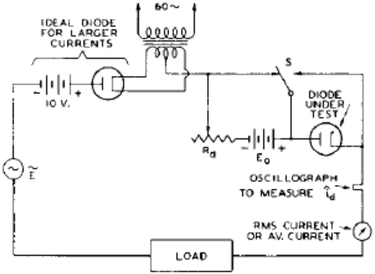


Fig. 3 - Half-wave circuit for measuring (d)\> rd, and |rd|.

When a measurement is being made, the resistor Rd is varied until the particular voltage or cur-rent under observation remains unchanged for both positions of the switch S. We observe (1)that it is impossible to find one single value of 1¾ which will duplicate conditions of the actual tube circuit, i.e., give the same values of peak, average, and rms current in the circuit;(2) that the ratio of these three "equivalent" resistance values of the diode varies for different combinations of circuit elements; and (3)that equivalent average or rms substitution resistances may have different values when the average cr rms current in the diode circuit is adjusted to the same value in different types of rectifier circuits. The "peak resistance" value obtained for a given peak current is found to be substantially independent of the type of circuit.

$$\hat{r}_d = \bar{r}_d = |r_d|$$

Diode Characteristics

A Course in Radio Fundamentals
Lessons in Radio Theory for the Amateur
By George Grammer, W1DF
http://www.rfcafe.com/references/qst/radio-fundamentals-vacuum-tubes-sep-1942-qst.htm

Experiment 21

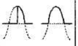
Apparatus: This experiment uses the plate power supply, tube board, test set, vacuum-tube voltmeter, and three 1- watt resistors, 25,000, 50,000 and 100,000 ohms. The circuit arrangement is shown in Fig. 3. Measurements must be made of the voltage applied to the tube and the current flowing in its plate-cathode circuit; the single test instrument can be used for both purposes by being shifted back and forth for each pair of readings. However, the small current consumed by the instrument when used as a voltmeter will cause the actual output voltage to be lower when the voltage is being measured than when the instrument is shifted to read plate current. Unless a separate voltmeter which can be left permanently in the circuit is available, it is advisable to use the v.t. voltmeter, thus avoiding the loading effect. The test instrument is therefore shifted between the plate circuit of the tube being tested and the plate circuit of the voltmeter tube.

The tube to be tested may be a 6H6, the diode section of a combination diode-amplifier tube, or simply a small triode such as the 6J5 with the grid and plate connected together to act as a single plate.

Λ. Waveforms and Equivalent Resistance Ratios for Practical Circuit Calculations

The form of the current pulse in practical rectifier circuits is determined by the power factor of the load circuit and the phase number. Practical circuits may be divided into two main groups: (a) circuits with choke-input filter; and(b) circuits with condenser-input filter. The current pulse in choke-input circuits has a rectangular form on which is superimposed one vapor diodes.

Table I

CONDUCTION TIME ANGLE φ	WAVE SHAPE	$\frac{\bar{i}_{p_\varphi}}{\hat{i}_p}$	$\frac{\lvert i_p\rvert_\varphi}{\hat{i}_p}$	3/2-POWER RECTIFIER CHARACTERISTIC			RECTANGULAR CHARACTERISTIC		
				$\frac{\bar{e}_{d_\varphi}}{\hat{e}_d}$	$\frac{\bar{r}_d}{\hat{r}_d}$	$\frac{\lvert\bar{r}_d\rvert}{\hat{r}_d}$	$\frac{\bar{e}_{d_\varphi}}{\hat{e}_d}$	$\frac{\bar{r}_d}{\hat{r}_d}$	$\frac{\lvert\bar{r}_d\rvert}{\hat{r}_d}$
CONDENSER-INPUT CIRCUITS									
≦ 20°		0.500	0.577	0.593	1.185	1.120	1.0	2.00	1.500
90° & 180°		0.637	0.707	0.715	1.120	1.057	1.0	1.57	1.272
130°		0.725	0.780	0.787	1.085	1.030	1.0	1.38	1.190
CHOKE-INPUT CIRCUITS									
180°		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

In this table, the designation the rms value of the current i-ρΐφ represents the rms during the conduction time. It follows that the relation

$$\hat{r}_d = 0.88\ \bar{r}_d = 0.93\ |r_d|$$

is representative for the group of condenser-input circuits containing high-vacuum diodes, and holds within ± 5 per cent over the entire range of variation in wave shape. The actual error In circuit calculations is smaller, as the diode resistance is only part of the total series resistance in the circuit.

EMISSION AND SATURATION OFOXIDE-COATED CATHODES

1. Oxide-Coating Considerations
The normal operating range of diodes (including instantaneous peak values) is below the saturation potential because the plate dissipation rises rapidly to dangerous values if this potential is exceeded. Saturation is definitely recognized in diodes with tungsten or thoriated-tungsten cathodes as it does not depend on the time of measurement, provided the plate dissipation is not excessive. The characteristic of such diodes is single-valued even in the saturated range, i.e., the range in which the same value of current is obtained at a given voltage whether the voltage has been increased or de-creased to the particular value.

Oxide-coated cathodes have single-valued characteristics up to saturation values only under certain conditions. The cathode coating has resistance and capacitance, both of which are a function of temperature, current, and the degree of "activation," and vary during the life of the tube. The conception of a "coating impedance” is essential in explaining many peculiar effects observed when testing and operating oxide-coated diodes in rectifier circuits and will be treated briefly.

The cathode coating is usually a mixture of carbonates (barium, strontium, calcium) which are "broken down" into oxides, metal atoms, and gases during the exhaust process. A highly emit-ting monatomic layer of barium on oxygen is formed on the surface of

If we substitute the values obtained in the Barkhausen equation we obtain

DSRi = 0.02*5.7*9.4 = 1.07 ~ 1.

Notes
Strictly speaking the anode voltage UA is always obtained from the applied voltage minus the difference between the electron work function voltages at the cathode phiC and the anode phiA:

UA = U – (phiA – phiC) .

Secondary phenomena caused by the Maxwellian velocity distribution of the electrons are also neglected.

The open-loop voltage gain μ = D^-1 is often quoted instead of the inverse amplification factor D.

When grid and anode are connected together, the greater part of the current flows through the grid.

$B1 = 8.36\ V^{-1}$ (150 mA)
$B2 = 9.84\ V^{-1}$ (140 mA)
$B3 = 11.24\ V^{-1}$ (130 mA)

and hence the cathode temperatures T:

$T1 = 1390$ K (150 mA)
$T2 = 1180$ K (140 mA)
$T3 = 1030$ K (130 mA)

The most probable velocities at different cathode temperatures are then:

$v_p(T1) = 204 \cdot 10^3\ m\ s^{-1}$
$v_p(T2) = 189 \cdot 10^3\ m\ s^{-1}$
$v_p(T3) = 177 \cdot 10^3\ m\ s^{-1}$

2. Fig. 6 shows the triode control characteristics measured. If we take working point A (UA, IA, UG) in the linear portion of the family characteristics we can determine all the characteristics of the tube. For A (100 V, 20 mA, 1 V) we obtain

$S = 10$ mA/V

for the “slope” S (gradient of the curve at point A).

The inverse amplification factor D is obtained by going from the 150 V to the 50 V characteristic through A and parallel to the UG-axis and reading off

$-dUG/dUA$, from which $D = 0.018$.

To obtain the tube resistance Ri, we go from the 50 V to the 150 V characteristic through A and parallel to the IA-axis and read off

dUA/dIA, from which $Ri = 5.85$ kohms.

the coating, which, when heated, supplies the electron cloud forming the space charge above the coating surface (see Fig. 4) ·The» coating itself consists of non-conducting oxide clumps or crystals (shown as shaded areas)interposed with metal atoms and ions (circles),which axe produced by high cathode temperature and electrolysis during the activation and aging process of the cathode.

The distances between these metal atoms or atom groups are very small. The current flow from the base material through the coating is effected by relay-emission from atom to atom or

particle to particle under the influence of electrostatic potentials. The coating is not con-ducting when cold. Electronic conduction through the coating is high when many metal relay chains, not broken by insulating oxides, have been formed,

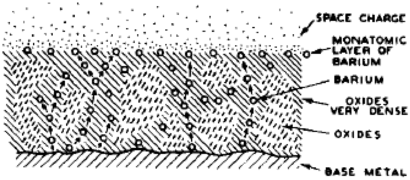


Fig. 4 - Structure of cathode coating.

and also when the electron emission is raised as a result of loosening the atomic structure by increased temperatures. Hence, the coating conductance may be represented by a large number of extremely close-spaced diodes in series-parallel arrangement, as shown in Fig. 4a

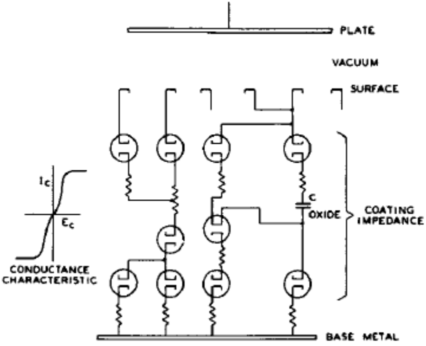


Fig. 4a - Representative diode network.

The coating activation is good when a fully emitting surface layer can be saturated without limitation of electron flow in the coating. This condition is indicated by a single-valued characteristic up to and beyond the saturation potential as shown in Fig. 5. In general, single-valued characteristics are obtained if the surface saturates before the coating conductance be-comes limited. (See temperature—limited conditions in Fig. 5).

The conductance of the coating may, however, limit the electron flow before the surface emission is saturated, and cause a peculiar voltage-current characteristic. Consider a high plate

where No is the total number of electrons and m (the restmass of the electron) is 9.11*10E-31 kg.

From this we obtain the most probable velocity

vp = sqrt4/pi * vp

and the mean velocity

vm = sqrt4/pi * vp

By fitting to exponential curves, using the expression

IA = A * e^B*UA

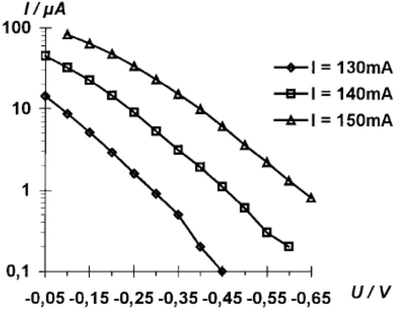


Fig. 5: Initial current of the diode at different heater currents.

we obtain from the measured values in Fig. 5 the exponents B, as follows:

The gradient of the IA/UG characteristic at working point A is called the “slope” S or “mutual conductance”:

$S = dIA/dUG$ at constant UA .

We obtain likewise the tube resistance Ri at working point A and at constant grid voltage:

$Ri = dUA/dIA$ at constant UG .

These three variables are interrelated by the Barkhausen equation (the “tube equation”):

$DSRi = 1$

1. If we plot the anode current against the (negative) and voltage semi-logarithmically in the initial current range of the diode we obtain a straight line of slope

$b = – e/kTc$ (cf. Fig. 5)

in accordance with

$\ln IA = \ln Io – |eUA/kTc|$,

where e = the electron charge = $1.60*10E\text{-}19$ As, and k = the Boltzmann constant = $1.38*10E\text{-}23$ VAsk^-1.

From this, we can calculate the cathode temperature

$Tc = – e/kB$.

For a Maxwellian distribution the electron velocites n are calculated in accordance with

$1/No\ dN/dv = 4/\sqrt{\pi}\ (m/2kT)^{3/2} * v^2 * \exp -mv^2/2kT$

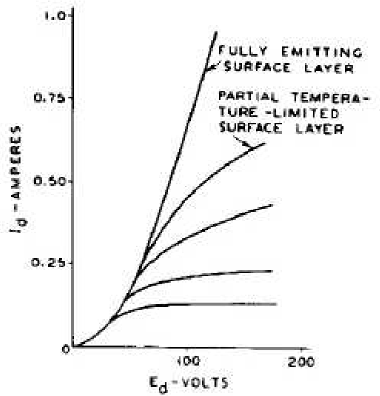
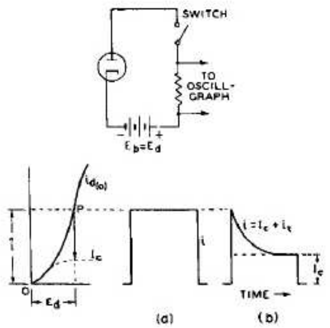


Fig. 5 - Single-valued saturation characteristic of diode with high coating conductance.

voltage suddenly applied over a periodic switch to a diode as in the circuit of Fig. 6. If the coating is not limiting, the current obtained is that at a point P on the corresponding diode characteristic. Hence, the current waveform in the circuit is as shown in Fig. 6a.



If the surface emission is assumed to be unchanged, but all free electrons have been moved. The oxide groups thus act like condensers in parallel to the coating resistance but with the peculiarity that their charge may be limited by hypothetical series diodes.

The coating resistance is extremely low* below saturation, due to the small spacing and high gradient in the "coating-diodes" but becomes in-finite when the conduction current is saturated; hence, the charging current must flow in the plate circuit (external) of the diode. The total plate current is, therefore, the sum of the conduction current Ic and the "transient" electron displacement current. The "coating transient” decays to zero like normal transients at a rate depending on the actual shunt conductance value and the total series resistance in the circuit(Fig. 6b). The decay can be changed by adding external resistance in the plate circuit. When the surface emission is good, i.e., as long as the total vacuum-space plate current is space-charge limited, the current will rise initially to the value

The emitted electrons first form round the cathode an electron cloud from which slow-moving electrons rebound and can thus return to the cathode. If we apply a positive voltage to the anode, some electrons are drawn out and the cloud becomes less dense as the anode voltage increases. In this part of the curve (space-charge region) the equation:

$$IA = P \cdot UA^{3/2} ,$$

applies, where P = the tube constant.

As the anode voltage is increased still further, in the end all the electrons emitted from the cathode are collected, the space charge disappears and the tube reaches saturation. Changing the anode voltage no longer brings about a corresponding change in the anode current.

If we insert another grid-like elektrode between cathode and anode we obtain a three-electrode valve, or triode. The anode current can be controlled by a voltage applied between the grid and the cathode. But as it is controlled also (but to a lesser extent) by the anode voltage UA, the two voltages combine to give a resultant control voltage

$$Uc = UG + D \cdot UA .$$

The so-called “inverse amplification factor” D is a constant at a given working point A and is defined by

$$D = dUG/dUA \quad \text{at constant } IA .$$

Since electron tubes generally work in the space-charge region, the anode current is essentially expressed by the space-charge formula

$$IA = P\,(UG + D \cdot UA)^{3/2}$$

Theory and evaluation

We distinguish three different regions in the current/voltage characteristic of a vacuum diode: the initial current, space charage and saturation regions.

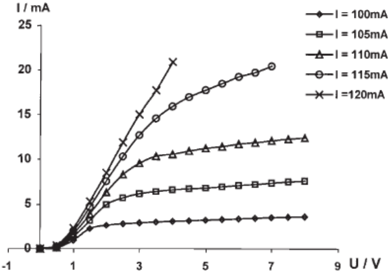


Fig. 4: Current/voltage characteristic of the diode for different heater currents.

A current still flows through the vacuum diode when the anode is negative with respect to the cathode (UA < 0). This current, which is known as the “initial current”, bears the following relationship to the (negative) anode voltage:

IA = I0 · exp – |eUA/kT|.

The electrons contributing to this current still have, as the result of their Maxwellian velocity distribution, sufficient kinetic energy after they have left the cathode to surmount the anode field and reach the anode.

(point P) determined by the applied potential, but will then decay to the saturation value determined by the coating conductance.

The condition of oxide-coated cathodes can, therefore, not be judged alone by their capability of furnishing high peak currents, but the rate of change in current flow, and hence the current waveform, must also be carefully considered, because the diode characteristic may not be single-valued. Fig. 7 shows characteristics which are not single-valued. These were taken within 1/120 of a second (l/2 of a 60-cyclesine wave) with a cathode-ray curve tracer.

2. Current Overload and Sputter

The degree of activation is not stable during the life of the cathode. Coating conductance and surface emission change. Factors affecting the change are the coating substances, the evaporation of barium depending on the base material, and the operating conditions to which the cathode is subjected. This life history of the cathode is the basis on which current ratings are established. Rectifier tubes especially are subject to severe operating conditions. If a diode is operated with too high a current in a rectifier circuit and its surface emission is decreased to the saturation value, then the tube voltage drop will increase rapidly, and cause excessive plate dissipation and destruction of the tube. Should the coating conductance in this diode decrease to a value which limits the demanded current, power is dissipated in the now-saturated "coating-diodes," with the result that the coating voltage drop and coating temperature are raised. The temperature rise may cause reactivation but also may become cumulative and melt the coating mate—

* Its magnitude depends on the number of series diodes and, hence, on the barium content and thickness of the coating material.

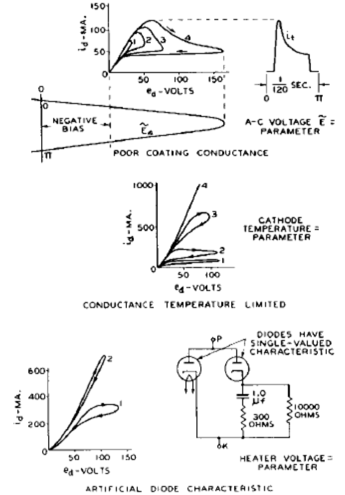


Fig. 7

Vapor or gas discharges may result from saturated coatings and cause breakdowns during the inverse voltage cycle. These breakdowns are known as "sputter," and destroy the cathode. Sputter of this type will occur more readily in diodes with long cylindrical electrodes and close spacing than in diodes with flat cathodes of narrow width and parallel—plane plates, because the activation gas can diffuse faster in the latter. A second type of sputter is caused by the in-tense electrostatic field to which projecting “high spots" on the

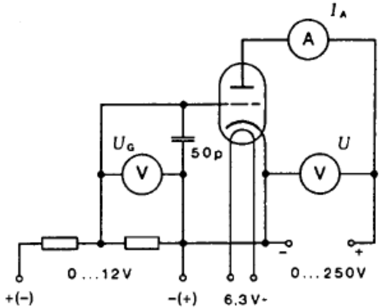


Fig. 3: Circuit for measuring the characteristic curves of a triode.

2. Construct the circuit shown in Fig. 3. As the tubes may oscillate in the VHF range if the wiring is not altogether satisfactory, connect a small capacitor between grid and cathode to short-circuit the high frequency.

Measure the anode current as a function of the grid voltage, both positive and negative, at various anode voltages (e. g. 50, 75, 100, 125, 150 V). Stop taking measurements as soon as the anode current exceeds 30 mA.

Because of the voltage drop across the internal resistance Ri of the ammeter, the anode voltage is represented by
UA = U – IA · Ri

Plot the IA/UG-characteristics (control characteristics) on a graph.

Plot the initial current characteristics at different heater currents also. To do this, reverse the polarity on the voltage source and the voltmeter multimeter and measure the anode current with the microammeter (multimeter).

Because of the voltage drop across the microammeter (multimeter) the anode current UA is:
UA = – (|U| + |IA · Ri|)

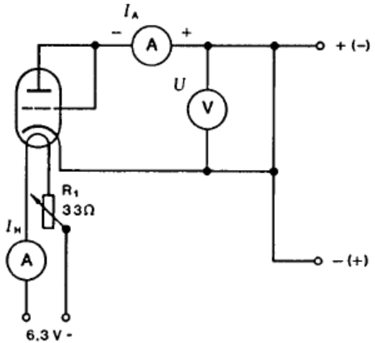


Fig. 2: Circuit for measuring the characteristics of a diode.

plate or cathode are subjected. These high spots are formed by loose carbon on the plate or large cathode—coating particles. The resulting current concentration causes these spots to vaporize with the result that an arc may be started.

3. Hot-Cathode Mercury-Vapor Diodes

The ionization potential Ej. of mercury vapor is a function of the gas pressure and temperature. It is approximately 10 volts in the RCA-83and similar tubes. A small electron current be-gins to flow at Ep = 0 (see Fig. 8), and causes ionization of the mercury vapor at Ep = Ej_. This action decreases the variational diode resistance Γρ to a very low value. The ionization becomes cumulative at a certain current value (rp = 0 at40 milliamperes in Fig. 8a), and causes a discontinuity in the characteristic. Hence, it is not single-valued within a certain voltage range. Beyond this range (see Fig. 8b), the slope (rp) of the characteristic becomes again positive until saturation of the emitter is reached.

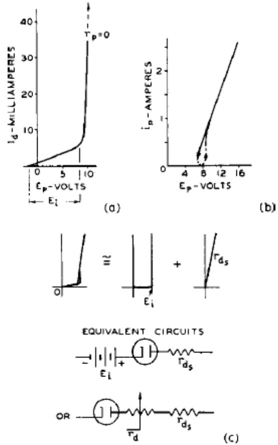


Fig. 8

For circuit analysis, the mercury-vapor diode may be replaced by a bucking battery having the voltage Ej_ and a fixed resistance,

$$r_{d_s} \cong \frac{\hat{e}_d - E_i}{\hat{i}}$$

as shown in Fig. 8c; or the diode characteristic may be replaced by an ideal rectangular characteristic and its equivalent resistance values and the series resistance rd^ as shown.

Characteristic curves of electron tubes (diode, triode)
PHYWE series of publications • Laboratory Experiments • Physics • PHYWE SYSTEME GMBH • 37070 Göttingen, Germany
http://www.nikhef.nl/~h73/kn1c/praktikum/phywe/LEP/Experim/4_1_10.pdf

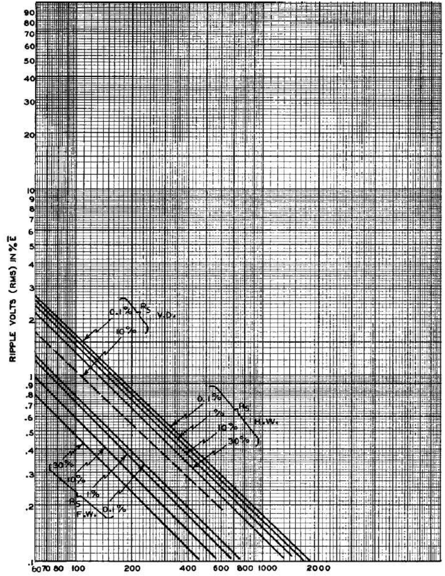
Principle and task
The IA/UA-characteristic curve of a diode is recorded at different heater currents and the cathode temperature and electron velocity determined therefrom. Mutual conductance, inverse amplification factor and anode resistance are determined from the characteristic curve of a triode.

Problems
1. To measure the anode current of a diode as a function of the anode voltage at different heater currents and to plot it on a graph. To calculate the cathode temperatures and electron velocities from the initial current characteristics.

2. To record the anode current of a triode as a function of the grid voltage at different anode voltages. To determine the mutual conductance, inverse amplification factor and internal resistance of the tube at a working point in the linear portion of the characteristic.

Set-up and procedure
1. Construct the circuit shown in Fig. 2. Connecting the anode and the grid gives tube EC 92 (triode) the properties of a diode.
The heater current and thus the cathode temperature can be set with the potentiometer R1.

Measure the anode current IA as a function fo the anode voltage UA at different heater currents (150–110 mA) and plot the results on a graph. The voltage drop across the internal resistance Ri of the ammeter (multimeter) must be taken into account, so that UA = U–IA · Ri. Stop taking measurements
when IA becomes greater than 30 mA.



The first representation is advantageous when making approximate calculations, as the equivalent diode resistance is then the substantially fixed value rdg. The value rds is in the order of 4 ohms. The low series resistance and the small constant voltage drop Ei are distinct ad-vantages for choke-input filters, as they cause very good regulation; the low resistance, how-ever, will give rise to enormously high storting transients in condenser-input circuits, in case all other series resistances are also small. Mercury-vapor diodes as well as high-perveance (close-spaced), high-vacuum diodes having oxide cathodes should, therefore, be protected against transient-current overloads when they are started in low-resistance circuits to prevent destruction of the cathode coating. The destruction of the coating in mercury-vapor diodes is apparently caused by concentration of current to small sections cf the coating surface and not by heat dissipation in the coating.

CIRCUIT ANALYSIS

The rectifier diode is a switch operated in synchronism with the applied a-c frequency. The diode alternately opens and closes the circuit. This action causes a series of transients in re-active circuits. According to the decay time of the transients, fundamental rectifier circuits may be classified into two principal groups: (l)circuits with repeating transients in which the energy stored in reactive elements decreases to zero between conduction periods of the diode; and (2) circuits with chain transients in which(a) the magnetic energy stored in the inductance of the circuit remains above zero value, and (b)the electric energy stored in the capacitance of the circuit remains above zero value. The much used "choke-input" and "condenser-input" circuits fall under the second group.

The complete analysis of rectifier-circuit operation requires more time than this lecture provides. It is based on the fact that the total current in a circuit is the sum of all steady-state currents and transient currents within the time between two switching operations. We will analyze briefly the operation in two important circuits, i.e., the full—wave, choke-input circuit, and the condenser-input circuit.

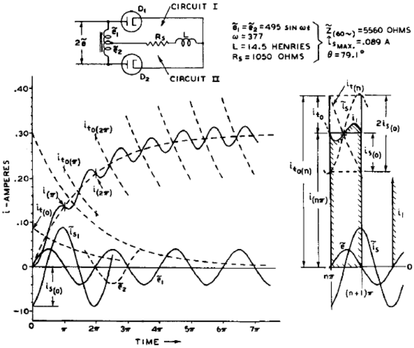
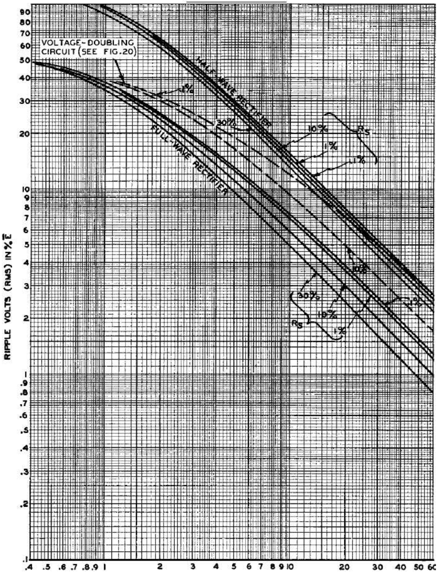


Fig. 9 - Full-wave choke-input circuit and its operation.

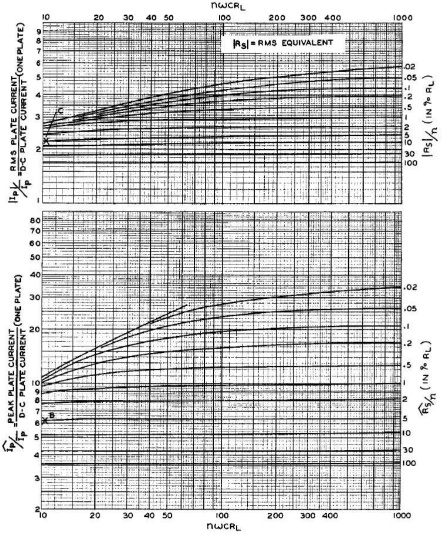
1. The Full-Wave Choke-Input Circuit

Circuit and operation are shown in Fig. 9. The construction is made by considering first one of the diodes shorted to obtain the phase relation of the a-c voltage e, and the steady-state current is, as shown. If we assume that the diode closes the circuit at the time e" = 0, a transient it with the initial value it0= -is(0) will flow in the circuit. The total current, i, is the sum of the currents is + 1¾. It starts, therefore, at zero and rises as shown until the second switching operation occurs at the commutation time t =η when the second diode receives a positive plate voltage. The total current, i,

RMS RIPPLE VOLTAGE OF CONDENSER INPUT LOAD CIRCUITS (lN ?°E) FOR VARIOUS VALUES OF Rs (GIVEN IN ?o R|_)
(MEASURED VALUES}



RELATIONS OF PEAK, AVERAGE, AND RMS DIODE CURRENT



after t = η is again the sum of currents xQ+ i-^, butte initial value if Q is increased by the value ï(π) still flowing in the circuit.

The current it0 increases, therefore, at every new switching time until the decay of the transient it(n) > during the time t = π, is numerically equal to the steady-state current rise 2Ïβ(0),as shown in Fig. 9* This leads to the equation for the final operating current at the n™ com-mutation time:

$$i_{n(\pi)} = -\tilde{i}_{s(o)} \frac{1 + \varepsilon^{-\frac{R}{2fL}}}{1 - \varepsilon^{-\frac{R}{2fL}}}$$

A broken line is shown connecting all commutation-current values. This line represents closely the average current I in the common circuit branch. The final average current ig, during the conduction time, and _the average current Iin the load resistance R, have the same value and are given by equation (7)_. The average plate current per diode is Ip =0.5I, since each diode conducts alternately, and passes a current pulse shown by the shaded area in Fig. 9. With the numerical values of the construction substituted in equation (7) and setting

$$\varepsilon^{-\frac{R}{2fL}} = 0.547$$

we obtain

$$i_{(n\pi)} = \bar{I} = 0.298 \text{ ampere.}$$

The described solution is illustrative in understanding starting and operating conditions of the choke-input circuit, but its accuracy is limited in cases of low power factor (large L or small R), since the decay terms in equation (7)become very small. The construction, however, shows the exact phase relations of current and voltage. The oscillogram in Fig. 10 was taken with the circuit values indicated in Fig. 9.

a. Critical Inductance — The analysis has shown that the transient currents in the particular case never decay to zero and are "chain transients.^ In practical circuits, the d-c load resistance R is shunted by a capacitance C. This does not affect the circuit performance, provided R does not increase beyond a critical value Rcr. Expressing this statement symbolically, we have

$$\bar{R} \leqq \bar{R}_{cr} = 1.5\ Z_{(2f)}$$

in which Z(2f) is the impedance of one branch circuit at double line-frequency. For large values of C,

$$Z_{(2f)} \cong 4\pi f L$$

$$\bar{R} \leqq 6\pi f L \quad \text{or} \quad L \geqq \frac{\bar{R}}{6\pi f}$$

$$L \geqq \frac{0.91\ |\tilde{E}|}{6\pi f\ \bar{I}}$$

where

$|\tilde{E}|$ = rms voltage of one-half the secondary winding

and

$\bar{I}$ = d-c load current.

The relation of equation (9) is characterized by the fact that the current i in the final operating condition (Fig. 9) has an a-c component which is so large that 1 becomes zero at one instant. Any further increase of this component caused by

discharged in series with the other condenser during the time of non-conduction of its associated diode. The analysis of operation is made according to the method discussed but will not be treated.

Table II

TYPE OF CONDENSER-INPUT CIRCUIT	nojCR	A η R	00	φ°	JL max	id	Upl ïρ
Half-Wave η - 1	0. 5	0	26. 5	153. 5	0. 335	3. 33	1. 69
	1.	0	45. 0	134. 0	0. 384	3. 68	1. 81
	2.	0	63. 4	111. 6	0. 486	4. 61	2. 00
	2. 26	0	66. 15	106. 4	0. 503	4-91	2. 02
	4-	0	75-9	87. 1	0. 623	6. 60	2. 24
	8.	0	82. 9	65. 1	0. 742	9. 86	2. 60
	16.	0	86.4	48. 6	0. 862	13-92	3. 00
	32.	0	88. 2	35-3	0. 930	19-90	3. 51
	64.	0	89. 1	25. 1	0. 996	27. 5 ?	4. 16
	2.	0. 10		121.	0. 434	4-48	1. 9
	2. 26	0.147	50.	123.	0.428	4. 42	1. 88
	4.	0. 05	65. I	99-3	0. 632	5. 28	2. 1
	4.	0. 10	56.	108. 4	0. 537	5. 14	2. 0
Full-Wave η - 2	1.	0	26. 5	142. 5	0.644	3. 47	1. 75
	2.	0	45. 0	121. 0	0. 678	4. 17	1. 90
	4-	0	63-4	92. 6	0. 740	6. 06	2. 17
	4-52	0	66. 15	86. 8	0. 744	6. 55	2. 24
	8.	0	75. 9	67. 0	0. 816	9-30	2. 55
	16.	0	83. 0	49. 0	0. 885	13. 74	3. 00
	32.	0	86.4	35. 6	0. 945	19-70	3. 50
	64.	0	88. 2	25. 4	0. 999	27. 1 ?	4-15
	4.	0.05		104.	0. 671	5-43	2. 05
	4-52	0. 0735	50.	105.	0. 636	5-35	2. 04
	8.	0. 05	56.	90.	0. 710	6. 20	2. 20
	30. 2	0.10	17. 9	100. 6	0.646	5-39	2. 08

the reversed problem to determine the magnitude of the applied voltage necessary to give a certain average voltage output for a given load. The series-resistance value Rg includes the equivalent average resistance rd
of one diode and the power-transformer resistances as reflected into one secondary winding. The characteristics were plotted from accurately measured values as their complete calculation required too much time. The measurements were made cti circuits of negligible inductive reactance. Series resistance values were determined accurately by the method shown in Fig. 2. Table II gives a number of calculated values which show the accuracy of the curves to be approximately 5 per cent or bet-ter.

In compiling the data for the current-ratio characteristics in Fig. 21, it was found that the three rectifier-circuit types could be shown by single family after a "charge factor" η was added to the_ product of the circuit constants ωl and to Rg as shown in Table II. The factor η is unity for the half-wave circuit. For the full-wave circuit, η is 2 because the condenser C is charged twice during one cycle. For the voltage-doubling circuit, η is 1/2 because the two condensers require together twice the charge to deliver the same average current at double voltage. The values in the table indicate that the factor η is actually not a constant. The mean value of the current ratios does, however, not depart more than approximately 5 per cent from the true value, the error being a maximum in the steep portion of the curves and decreasing to zero at both ends. The upper section of Fig. 21 shows the ratio of rms current to average current per diode plate. This family is of special interest in the design of power transformers and for computation of diode plate dissipation.

Fig. 22 shows the rms value of the ripple voltage across R^ in per cent of the average voltage.

The voltage-doubling circuit shown with the other two condenser-input circuits in Fig. 17 maybe regarded in principle as a series connection of two half-wave rectifier circuits. Each con-denser is charged separately during conduction time of one diode, but is

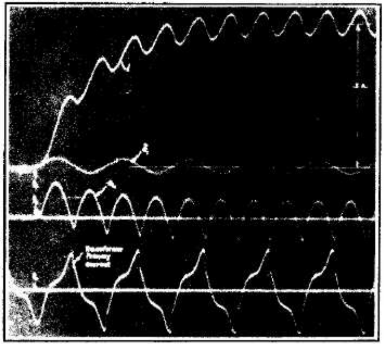
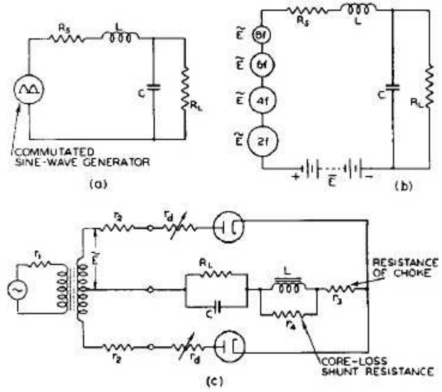


Fig. 10 - Oscillogram taken with circuit values in Fig. 9.

decreasing L still further will, therefore, open the diode circuit and hence interrupt chain-cur-rent operation. The circuit then becomes a type of condenser-input circuit and the output voltage E rises beyond the value given by the equivalent circuit for the chain-current operating range.

b-_Equivalent Circuit _for__ the Chain-^ur-rent_0^erating_Range — Commutation of the cur- rent in the chain-current range occurs at the instant when the supply voltage passes through zero. The voltage energizing the common branch of choke-input rectifier circuits has the form of a_ commutated sine wave for any load value R = Rcr· Since the circuit is never interrupted, currents and voltages may be considered steady-state components in a circuit energized by the equivalent commutated sine voltage as shown in Fig. 11a. The single generator in Fig. 11a may



be replaced as shown in Fig. lib by a battery and a series of sine-wave generators having frequencies and amplitudes, as given by the following equation of the commutated sine wave.

$$\tilde{e} = \frac{2\,\tilde{e}_{max}}{\pi}\left[1 - \frac{2\cos 2f}{1\times 3} - \frac{2\cos 4f}{3\times 5} - \frac{2\cos 6f}{5\times 7} - \dots\dots\right]$$

The d—c component or battery voltage is the total average voltage E discussed in the preceding sections .
Some useful relations of voltage components are:

RELATION OF APPLIED AC VOLTAGE TO DC OUTPUT VOLTAGEIN VOLTAGE-DOUBLING CIRCUIT
in farads ,rl in ohms

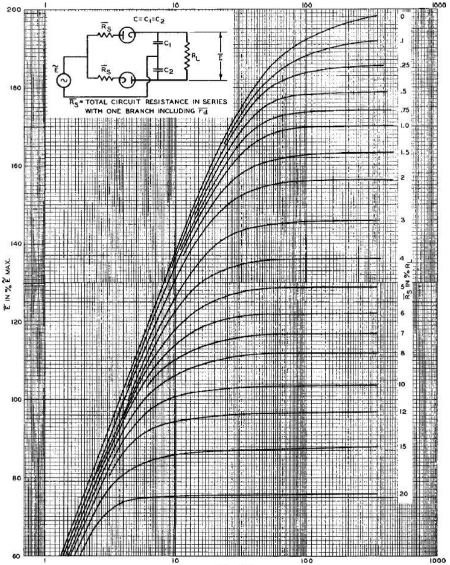
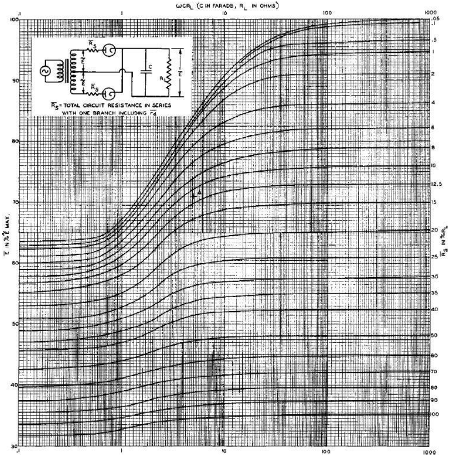


Fig. 20

RELATION OF APPLIED AC VOLTAGE TO DC OUTPUT VOLTAGEIN FULL-WAVE RECTIFIER CIRCUIT



Line voltage induced in one-half of the secondary winding (rms)	$\lvert\tilde{E}\rvert = 1.1\ \bar{E}$
Total average voltage	$\bar{E} = \begin{cases} 0.90\ \lvert\tilde{E}\rvert \\ 0.637\ \tilde{e}_{max} \end{cases}$
Voltage of frequency 2f (rms)	$\lvert\tilde{E}\rvert_{2f} = \begin{cases} 0.424\ \lvert\tilde{E}\rvert \\ 0.471\ \bar{E} \end{cases}$
Voltage of frequency 4f (rms)	$\lvert\tilde{E}\rvert_{4f} = \begin{cases} 0.085\ \lvert\tilde{E}\rvert \\ 0.0945\ \bar{E} \end{cases}$
Total choke voltage (rms)	$\lvert E\rvert_{L} = \begin{cases} \sqrt{\lvert\tilde{E}\rvert^2 - \bar{E}^2} \\ 0.482\ \bar{E} \end{cases}$

The current components in the common circuit branch are calculated from the above volt-ages divided by the impedance of one branch-circuit at the particular frequency. Because the current is commutated every half-cycle of the line frequency from one to the other branch-circuit, the average current in each diode circuit is one-half of the total average current; and rms values of currents or current components in each branch-circuit are obtained by multiplying the rms current values in the common circuit branch by 1/ /2. The peak current in each diode circuit has the same value as in the common circuit branch.

Average load current
$$\overline{I} = \frac{\overline{E}}{R_s + R_L}$$

Average plate current (per diode)
$$\overline{I}_p = 0.5\ \overline{I}$$

Double-frequency current (rms) in common circuit branch
$$|\tilde{I}|_{2f} = \frac{|\tilde{E}|_{2f}}{Z_{(2f)}}$$

Total current (rms) in common circuit branch
$$|I|_L = \sqrt{\overline{I}^2 + |I|^2_{2f}}$$

Rms diode current or rms current per transformer winding
$$|I|_d = \frac{|I|_L}{\sqrt{2}}$$

Peak diode current
$$\hat{i}_d = \overline{I} + (|\tilde{I}|_{2f} \times \sqrt{2})$$

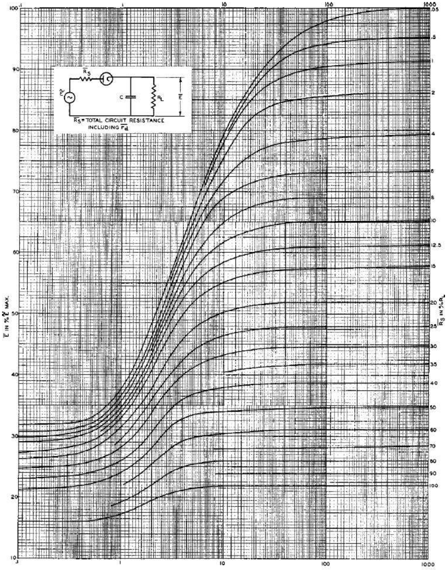
The total power dissipated in diode and load circuits of the practical secondary circuit shown in Fig. 11c is the sum of the power losses in the circuit resistances. In equation form, it is
Total Power = Series-Resistance Loss
+ Choke-Core Loss
+ D-C Power in Load

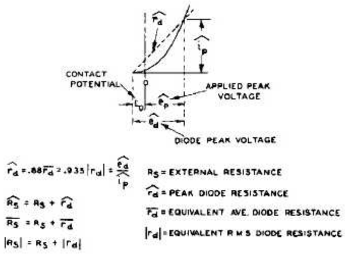
The plate dissipation per diode is given by:

$$P_d = 0.5\ |I|^2_L \times |r_d|$$

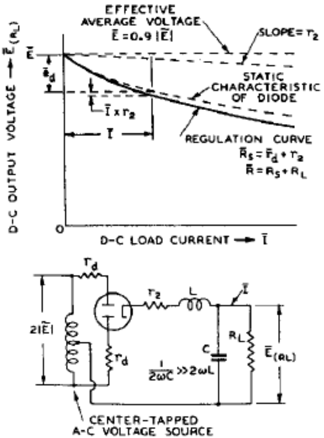
$$P_d = 0.5\ |I|^2_L \times \frac{\overline{e}_d}{\overline{I}}$$

RELATION OF APPLIED AC VOLTAGE TO DC OUTPUT VOLTAGE IN HALF-WAVE RECTIFIER CIRCUIT. UJCRL
(c IN FARADS , RL IN HMS)





where ed is the diode voltage taken from the static_diode characteristic at the output-current value I.



The regulation of choke-input circuits is determined by the_ total series resistance Rg, since the voltage E in the circuit is constant in the useful working range for an energizing-c voltage of constant value._ Thus, the regulation curve has the slope Rg (see Fig. 12),which includes the diode resistance.

The curve is correct for constant voltage e and beyond the critical-current value. In practical circuits, the voltage source e has a certain equivalent resistance, which must be added to r2. The equivalent internal resistance of the rectifier circuit as a d-c supply source is the slope of the regulation curve at the current value under consideration. This value should be used for steady-output conditions only, since the reactance in the load circuit cause transients at the instant of sudden load changes.

2. The Condenser-Input Circuit

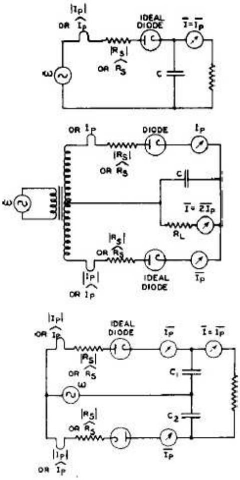
In rectifier circuits with shunt-condenser-input loads, the condenser is alternately charged and discharged. In the final state of operation, charge and discharge are balanced. The graphic analysis of such circuits is comparatively simple and readily followed. Formulas for the calculation of specific circuit conditions are easily derived from the constructions.

a._Circuits. _Without_ Series Resistance_ —
The graphic analysis of a half-wave rectifier circuit without series resistance (Rs) is illustrated in Fig. 13· Steady-state voltage e and current is are constructed on the assumption that the diode is shorted. The steady-state condenser voltage e'c coincides with e" because Rg = 0.
The diode timing is as follows: The diode opens the circuit at point 0 when the diode cur-rent becomes zero. The condenser voltage at this instant has the value

$$e_{C(o)} = \tilde{e}_{max} \sin \Theta$$

Since the condenser-discharge circuit consists of C and l, the condenser voltage decays exponentially as shown. At point C it has become equal to the energizing voltage e'. The diode be-comes conducting and closes the circuit. Because there is no potential difference between the steady-state voltages e and ec at this or any instant, the condenser does not receive a transient charge. The current, therefore, rises instantly to the steady-state value as shown on the i s curve and then decreases until it is zero at point 0.

(sine wave) for half-wave, full—wave, and voltage-doubling circuits. They permit the solution of



these transients analytically but the method is too involved to discuss in this lecture. The transients e-t and 1¾ in Fig. 15a prevent voltage and current from following the steady-state wave-forms. When Rg is large, they do not decay to zero within one cycle and, therefore, require additional steps in the graphic solution. The oscillogram shown In Fig. 16 checks the graphical construction of Fig. 15·

Fig. 16 — Oscillogram verifying graphical construction of Fig. 15·

c Generalized _operation__ Characteristics^{Steady-State^ Operation) — It has been shown that the conduction angle φ is a function of the circuit constants in condenser-input circuits. The section of the energizing voltage e utilized during conduction time has, therefore, no fixed value as in choke-input circuits where φ = 180°and where the voltage e during φ is a half-sine wave. It is, therefore, not possible to derive general equivalent circuit for condenser-input circuits which contains a voltage source of fixed wave shape and magnitude.

Steady-state conditions as well as transients are controlled by the circuit constants, which are contained in the product wl, The angle φ depends on the relative magnitudes of R^ and Rg and is, therefore, described in general is also the ratio s /^l^3^1011"1· General curve families may thus _be evaluated which show the dependent variables E, i, and I in terms of ratio versus the independent variable coCR^ various parameter values Rg/R^. The series resistance Rg includes the equivalent diode resistance which is evaluated by means of equation (6), because the current wave is periodic in the final operating state. The reasoning leading to equation(6) is not applicable to a single transient, as obtained for starting conditions of rectifier circuits.

Generalized characteristics have been evaluated for the three types of circuits shown in Fig. 17. The characteristics in Figs. 18, 19, and20 show the average voltage E across the load resistance Rl as a function of co CRt and Rg in per cent of the applied a-c peak voltage

The timing of the full-wave circuit in Fig.1Λ is quite similar. The time for the condenser discharge through l is reduced since e0 meets the positive half-cycle 6¾ and thus closes the circuit through D2· Point C in Fig. 14. is located at a higher value of e than in Fig. 13· The conduction angle φ is consequently reduced al-though C, R l, and Θ have the same values in both circuits. The average current in the full-wave circuit is, therefore, smaller than twice that of the half-wave circuit.

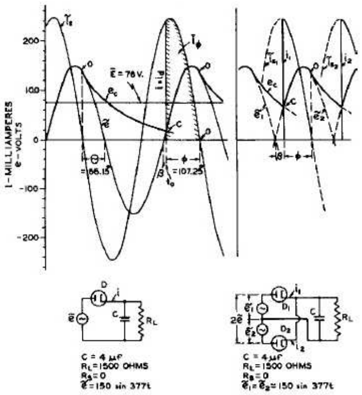
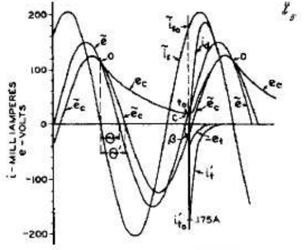
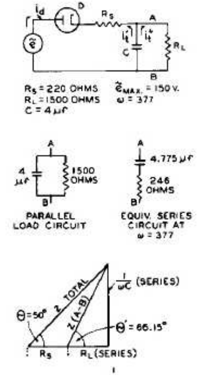


Fig. 13 (left) - Half-wave, condenser-input circuit without series resistance.
Fig. 14 (right) - Full-wave, condenser-input circuit without series resistance.

b. Circuits With_ Series _ Resistance —

In circuits with series resistance, the steady-state condenser voltage ec
does not coincide with the supply voltage e, as illustrated in Figs. 15a and15b. Phase displacement and magnitudes of cur-rent and voltage under steady-state conditions are required for analysis of the circuit and are computed in the conventional manner. The parallel circuit C II Rj, is converted into an equivalent series circuit to determine the angles
Θ and©' lay which Γ8 is leading e and ec, respectively. The steady—state condenser voltage Za in the parallel circuit equals the voltage across the equivalent circuit as shown by the vector diagram in Fig. 15b.





The diode opens the circuit at the instant id = 0. For circuit constants as in Fig. 15, the diode current id substantially equals Γ3 at the time of circuit interruption because the transient component i^' of the current has decayed to a negligible value. Point 0 is thus easily located. In circuits with large series resistance, however, id = 0 does not coincide with ïβ=0 due to slow decay of the transient. In both cases the condenser voltage each (0) equals the voltage (o) at the time 0, because id = 0 and consequently there is no potential difference on Rg. The condenser voltage decays exponentially ai Rj, from its Initial value at 0, as discussed for circuits with Rg = 0, and meets the supply voltage e" against point C. At this instant (tQ), the diode closes the circuit. Current and voltage, however, do not rise to their steady-state values as in circuits with Rg = 0, because the steady-state volt-age e"c(o) differs from the line voltage e(0) by the amount e"c(0) = ^s(o)x%· This demanded potential change on the capacitance causes transients. It is possible to determine the value of