THE SAGA OF THE VACUUM TUBE

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Part 8. Covering the period during which the elements of the triode tube were redesigned to obtain increased performance.

WHILE Fleming was working in England and the de Forest Audion was being put into use in the United States, important work in electronic research was being done in Continental Europe. To go back a little, in 1895 Roentgen announced the discovery of the mysterious penetrating rays which, because their properties were not at that time understood, were called *"X" rays*. As was to be expected, this announcement sent the European savants off into new fields of exploration. One of the earliest finds was that by Becquerel of the radioactivity of uranium, whose rays, like X-rays, produced electric conductivity in air and other gases by ionization.

The earliest of the discoveries in the field of thermionic rectifiers, those of Arthur Wehnelt, have already been discussed and will not be repeated.

At the time Fleming and de Forest were laying the foundations of the great tube art in connection with their work on wireless detectors, von Lieben in Vienna was working on the problem of the telephone relay or amplifier.

Robert von Lieben, the son of wealthy parents, was born in Vienna in 1878. Although he grew up in intellectual surroundings he always disliked formal education, and preferred to educate himself in his own way. Very early in life he showed an aptitude for scientific investigation. At that time electrical engineering was a promising field and it beckoned to von Lieben. He learned the practical phase of this work in the Siemens-Schuckert works in Nuremberg, and then went to the University of Goettingen for physical and chemical research, under the renowned chemist, Nernst.

Returning from Goettingen in 1903 von Lieben set up his own physical laboratory in his parental home. During the years 1905-1910 he developed the *"amplifying relay"* with which his name is associated. With the aid of his father he purchased a telephone factory in Olmutz (Moravia). This concern brought him into association with Eugen Reisz. Von Lieben was much intrigued with the idea of producing a telephone relay. His former professor, Nernst, said of him "No problem impressed him so much as the construction of the telephone relay, or more commonly expressed, a device which is capable of amplifying without distortion small changes in electrical currents".[143]

In his Vienna laboratory in 1905 von Lieben checked Wehnelt's experiments with the oxide-coated cathode, and remembering the cathode-ray beam ar-

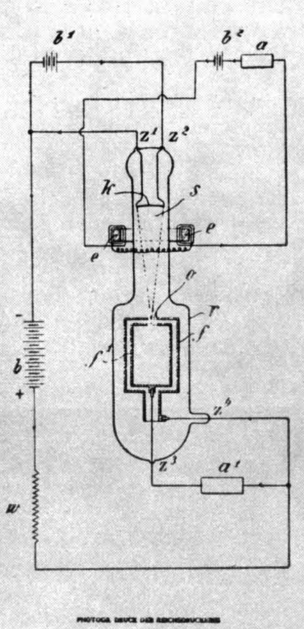

Fig. 49.

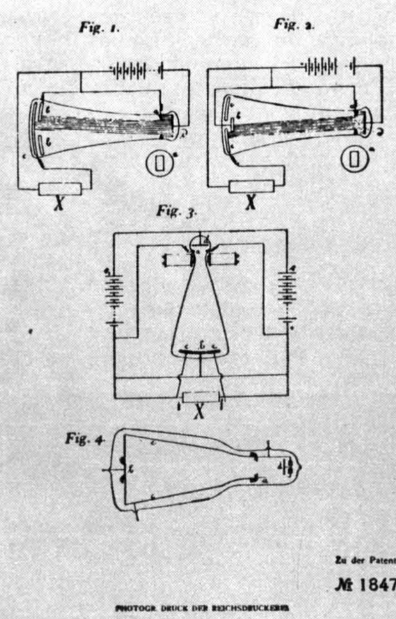

Fig. 50.

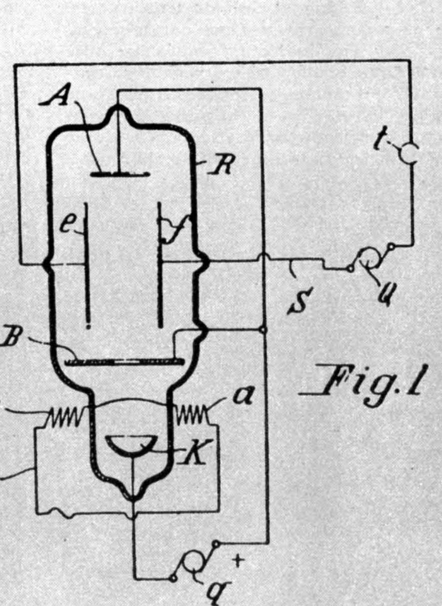

Fig. 51.

rangement used by Braun* in 1897,[144] hit upon the idea of constructing a telephone relay using this combination. He started by controlling the rays magnetically, although electrostatic control of the cathode-ray beam was known at that time. His work soon produced results, and on March 4, 1906 he applied for a German patent[145] on a device which he called a "Cathode Ray Relay." The object of the invention was to enable current variations of small energy at the input terminals to release current variations of greater energy at the output terminals, with frequency and waveform corresponding to that of the input. The patent states that the device is particularly suited to telephone applications such as "relaying of speech to great distance, cable telegraphy, wireless telephony, strengthening of speech, etc."

The diagram given in the patent is shown in Figure 49. It shows magnetic control of the cathode rays, but the patent states that either electromagnetic or electrostatic control may be used.

In this tube, which was described as *"highly evacuated,"* von Lieben used a cathode which was in the form of a hollow mirror, covered with calcium oxide. This cathode was described as being heated by the battery "b¹". The hollow mirror focused the cathode rays on the inner of two concentric cylindrical anodes "f" and "f¹", through the aperture "o". The focus of the rays was altered by the input current flowing in the magnetic field coils "e", which caused more or less of the cathode rays to impinge upon the inner cylinder and thus vary the inner anode current, which also flowed through the load device "a¹". The battery "b" provided the energy in the anode circuit.

Even before this von Lieben patent was published two other men, Max Dieckmann and Gustav Glage of Strasburg, applied on October 10, 1906, for a patent[146] on another type of cathode ray relay which they claimed was capable of giving an output absolutely proportional to the input. In their patent application reference was made to the von Lieben arrangement.

Several possible structures were shown in the diagrams forming a part of the Dieckmann and Glage patent. These diagrams are reproduced in Figure 50. The cathode was a plane and said to be "conveniently treated in order to facilitate the emission of electrons," and the aperture in the diagram "a" was used to obtain a "sharply defined bundle of cathode rays of comparatively large, preferably rectangular cross-section." The axes of the deflecting coils were placed at right angles to the direction of flow of the cathode rays, unlike the von Lieben arrangement in which the magnetic field was parallel to the cathode-ray beam. The magnetic field in the Dieckmann and Glage device

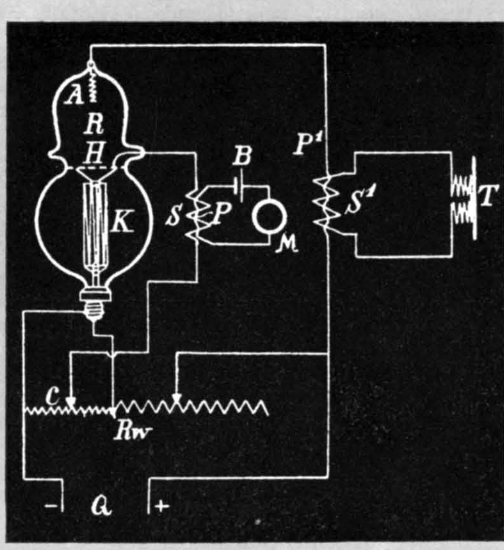

Fig. 52.

Fig. 53.

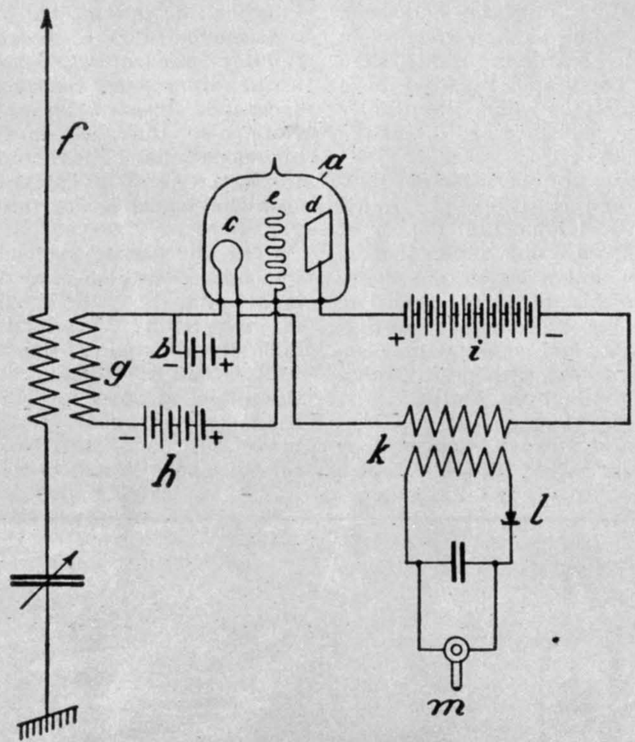

Fig. 54.

acted to deflect the cathode-ray beam from side to side, instead of altering the focus, as von Lieben's did. By means of this deflection more or less of the beam could be caused to fall on the center or side plates, and the currents in the individual anode circuits could thus be modulated.

This relay had the elements of the modern "electron gun" and the configuration shown in the middle figure was even capable of "push-pull" operation, provided the proper auxiliary apparatus was used at "X". The patent also states that the longer the distance from the diaphragm to the screen the greater would be the sensitivity, but that the shorter the distance the lower the operating voltage required. The structure shown in the bottom figure of the patent was given to illustrate how the electrodes might be arranged so as to keep the electron path free from the influence of interfering phenomena. Hence the device may also be said to be self-shielded. Whether the electron emission was obtained by heating the cathode or not is not stated.

About the same time (1908) Otto von Baeyer of the University of Berlin described[147] a three-electrode tube consisting of a central filamentary cathode rendered incandescent by a

* *This Braun tube was the first embodiment of the cathode-ray oscillograph tube, the development of which will be the subject of a subsequent article.*

battery, surrounded by a cylinder of wire gauze, which in turn was surrounded by a cylindrical sheet metal anode. The whole was contained in a cylindrical glass tube which was partially evacuated, to a pressure of about 0.01 mm. mercury. This structure resembled that of some of the triodes which were still years in the future. Von Baeyer used this device to measure the ionization produced by cathode rays emitted from the filament. For this work the inner gauze cylinder was operated at a potential positive to the cathode and the outer cylinder at a potential negative to the cathode, in order to collect on the outer electrode the positive ions produced by the cathode rays in their passage through the space between the gauze electrode and the outer cylinder. Had the potentials been reversed the tube would have been an amplifier.

In the meantime von Lieben continued to strive for a better telephone relay. He was hindered in this work by extensive illness. While serving his year of military duty he had been catapulted from a horse onto a wooden fence, sustaining injuries to his chest. This later resulted in a glandular abscess which eventually brought about his death in 1913, at the early age of 35.

Reisz did most of the later development work on the cathode-ray relay, although several important details of later designs[148] are due to von Lieben, who was very active despite the severe pain due to his physical condition. Later these two were joined by Sigmund Strauss, and subsequent German patents on the cathode-ray relay were issued to all three jointly.

The next development of von Lieben, Reisz, and Strauss is covered by German patent D.R.P. 236716[149], which bears the application date of September 4, 1910. The diagram of this patent is reproduced in Figure 51. It will be noted that the structure bears much resemblance to that disclosed by Dieckmann and Glage in the patent previously discussed. The current to be amplified flows through the coils "a" and the magnetic field thus set up acts on the cathode ray stream. This is described as causing changes in the ionization of the attenuated gas in the open space between the plates "e" and "f". The diaphragm "B" is used to screen the cathode rays in such a way as to prevent their striking the plates "e" and "f". The load device is shown as a telephone in the circuit composed of the generator "Q", telephone "t", plates "e" and "f", and the ionized space between the plates. Note that the hollow mirror type of cathode is still retained. No method of heating the cathode is shown, but the patent specification states that:

"The material used and the temperature of the cathode "K", as well as that of the gas in the discharge tube are so chosen that, with comparatively small potential difference, emission of the cathode stream results."

Note also that the inventors have abandoned the "high vacuum" referred to in the previous patent, and now speak of ionization of the attenuated gas.

"The difficulty of producing the hollow mirror cathode, the non-uniform emission of the cathode rays from the glowing oxide, and particularly the difficulty of maintaining a constant vacuum in the discharge tube were the main reasons" which motivated further development of the 1906 device[148]. From D.R.P. No. 236716 described above it will be seen that the difficulties related to the "high vacuum" were overcome by the utilization of the ionization of a rarefied gas instead of depending on pure thermionic emission.

The next patent issued to these inventors was German patent D.R.P. No. 249142[150]. It bears the application date of December 20, 1910, and is described as a supplement to D.R.P. No. 236716. In this specification, reference is made to the work of de Forest and his use of an "auxiliary cathode" in the form of a sieve or grid. Concerning de Forest's device the statement is made that "the currents to be magnified were led through the cathode and said electrode (grid or sieve)".

This statement would seem to indicate that von Lieben and his associates recognized the Audion structure to be an amplifier, even though de Forest himself had been unable to make it perform this function.

The invention, referred to in this patent, (D.R.P. No. 249142) is described as a modification of the one shown in the previous patent (D.R.P. No. 236716). The modification consisted of the use of electrostatic control by means of an auxiliary electrode to produce the variations in the amplified current, instead of using the variable ionization previously obtained by electromagnetically bending the cathode-ray stream. This auxiliary electrode is described as a "grid, grating, or mesh" so constructed that it "perfectly divides the cathode space from that of the anode". See Figure 52. The effect of this auxiliary electrode is said to be that of modifying the resistance of the space between the cathode and the anode. This results in variations of the anode current corresponding to changes in the resistance of the space.

It will be observed that there is provided, in the potentiometer "c" a means of adjusting the steady state potential of the grid. Concerning this adjustment the patent says:

"The adjustable potential thus brought to bear on H, has been found to be of the greatest importance in the successful operation of the relay, because a proportional variation of resistance of the gas discharge tube happens only at a certain definite value of potential difference, and this depends on the gas pressure and temperature of the cathode, etc."

Figure 53 shows a von Lieben tube of this type, made in 1911.

The diagrams show, in all but one case, a ribbon cathode looped back and forth in the manner of an incandescent lamp filament of that time. This ribbon is oxide-coated, and is heated by a battery. In one suggested form, not shown in Figure 52, the hollow mirror cathode and external magnetic control are retained.

Mention has been made above of the reference in this patent specification to the work of de Forest, and the recognition by von Lieben of the potential

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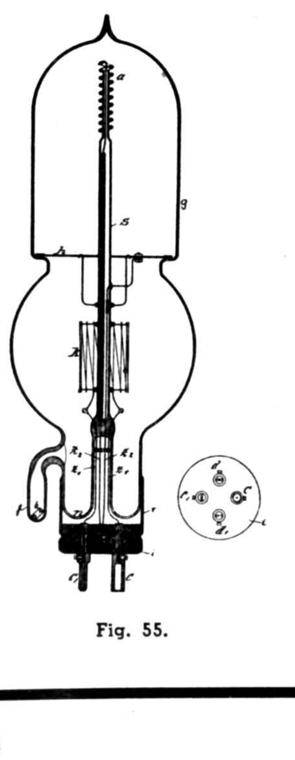

Fig. 55.

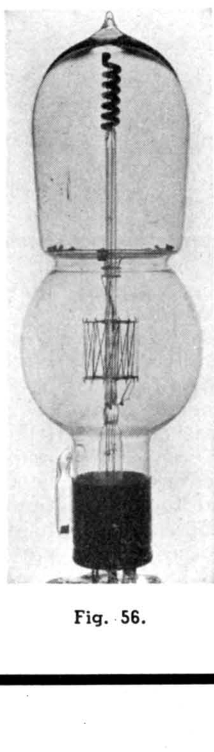

Fig. 56.

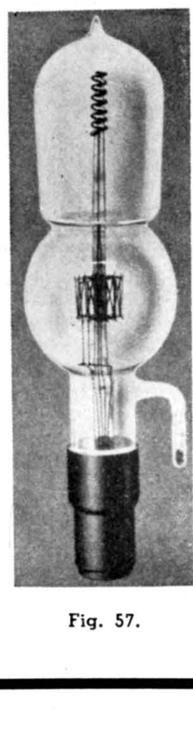

Fig. 57.

Saga of Vacuum Tube

(*Continued from page 28*)

amplifying properties of the Audion. As has been noted in a previous article, de Forest had not up to this time succeeded in utilizing the Audion for this purpose. This may possibly have been due to the use of improper coupling impedances, the use of radio frequency coils and condensers, in trying to make it operate as a low frequency amplifier.

Otto von Bronk, a Telefunken engineer, was more successful in this respect, and in 1911 obtained a German patent (D.R.P. No. 271059)[151] on the use of the de Forest "hot cathode tube" as a *high frequency* amplifier. The arrangement used by von Bronk is shown in Figure 54. He also obtained French, United States, Austrian, and British patents for the arrangement.[152]

The final form of the von Lieben tube, which in time came to be known as the "LRS Relay" or "LRS Repeater", is shown in German patent D.R.P. No. 264554,[153] the application date of which is October 15, 1912. This patent was issued to the Allegemeine Elektricitäts Gesellschaft in Berlin, which had with the Telefunken Company acquired the rights to the inventions of von Lieben and his associates a short time before.

The story of the development of this Repeater was told by Reisz in an article published in 1913,[148] and his description of the device, which is shown diagrammatically in Figure 55, is as follows:

> *"g is the evacuated glass tube in which the three electrodes (cathode k, auxiliary electrode h, and anode a) are mounted. The auxiliary electrode extends over the entire cross-section of the tube and permits of current flow between the main electrodes through small openings, the main electrodes being connected to a direct current source. The cathode k consists of a thin platinum strip, wound in a zig-zag fashion upon a glass rod, the metal surfaces being covered with a thin layer of barium and calcium oxides. The cathode is brought to a bright red heat (1000° C) by means of the battery of 30 volts."*

Further details from other sources are as follows.[154] The cathode consists of a strip of platinum about 1 meter in length, 1 mm. wide, and 0.02 mm. thick. The apertures in the auxiliary electrode (grid), which is an aluminum disc, are 3.5 mm. in diameter. An amalgam of mercury is contained in the small side tube. This is used to enable the operator to maintain the pressure in the main tube at the proper level (about 0.01 mm. mercury). Mercury vapor could be introduced, when needed, by heating the amalgam in the side tube. The anode was a spiral of aluminum wire 2 mm. in diameter. The anode battery was 220 volts, the anode current 10-15 milliamperes, and the cathode heating current was about 2 amperes. The amplification factor was approximately 33, and a useful life of 1000-3000 hours was claimed.

In the earlier LRS Relays the bulb was about 18 inches high and had a maximum diameter of about 4 inches. Later a smaller bulb about 8 inches high, with corresponding reductions in the other dimensions, was made.[155] There were two types of bases. In one of these all connections were made through bayonet pins which were so arranged that the tube would not be inserted in an incorrect manner into the socket used. Figure 56 shows a specimen of the larger LRS Relay, with a base of this type. Figure 57 shows the same type of tube but with a different base.

The LRS Relay was used for a time as a telephone repeater in Germany, but was never satisfactory. It had several disadvantages. It was, like all ionization devices, undesirably noisy. The filament was subject to bombardment by the positive ions of the mercury vapor, which tended to knock off the oxide coating. Variations in the operating characteristics caused by external influences, such as temperature changes, were excessive. It was very sensitive to extraneous voltages which, if very great, caused paralysis of the tube. Most of these disadvantages are, however, common to all devices which employ mercury vapor. The introduction of this vapor had the effect of reducing the internal impedance of the device, and permitting the use of larger anode currents than had previously been obtained in vacuum tubes. It also simplified the design of the necessary auxiliary apparatus, such as input and output transformers.

When the LRS Relay was in operation the upper portion of the bulb, above the perforated intermediate electrode (grid), was filled with the blue glow of the ionized mercury vapor, except for a dark space just above the grid. This tube was usually operated with a positive potential on the grid, which was adjusted by means of a potentiometer. The most satisfactory functioning was usually obtained when the grid potential was adjusted so that the dark space extended from 1 to 2 cm. above the grid.[156] Some of these tubes had a graduated scale etched on the side of the glass bulb, extending upward from the grid. This was probably used as a guide in adjusting the height of the dark space.

The LRS Relay was made in two sizes, as has been noted before, and also in two types. One type had the electrode construction described above, the other was similar except that the perforated aluminum disc used as a control element was replaced by a fine wire-mesh grid.[157] It is not known to the author whether both types were made in both sizes or not. The tube with the fine mesh grid was intended for use as a "weak current" amplifier, and the other type, although similar, as a "strong current" amplifier.

Some of the difficulties which were experienced in the use of this amplifier in practice were overcome by enclosing the tube in a temperature regulator, as shown in Figure 58. This arrangement was made the subject of a German patent in 1914.[158] It was a makeshift solution, however, which only partially overcame the difficulties.

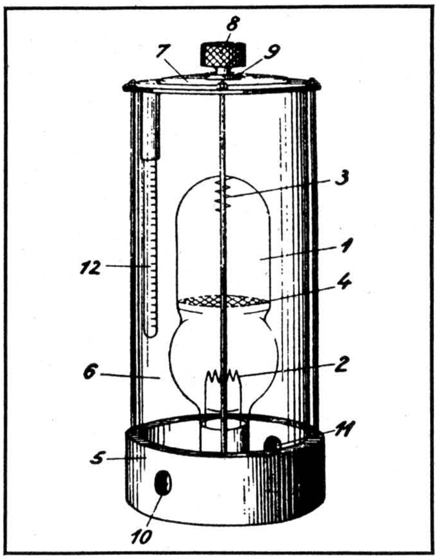

Fig. 58.

A short time later the Telefunken Company abandoned the gaseous tube and brought out a smaller tube with a tungsten filament, and a high vacuum.[159] This and later German high vacuum tubes will be treated in a subsequent article.

It is interesting to note, in passing, that von Lieben and his gaseous ionization tube have been honored by the Austrian Government by being pictured on a postage stamp. The stamp is one of the Charity Series of Commemorative Semi-Postals, issued in 1936. (Scott No. B131)

Concerning the work done in thermionics in other parts of Europe, the author has been able to find record of only two cases of such activity. The first is that of Eric Magnus Tigerstedt of Copenhagen, who, in 1914, obtained a German patent (D.R.P. No. 314085)[160] for a "relay for undulatory currents." A United States Patent covering the same device, and bearing the application date October 19, 1916, was issued

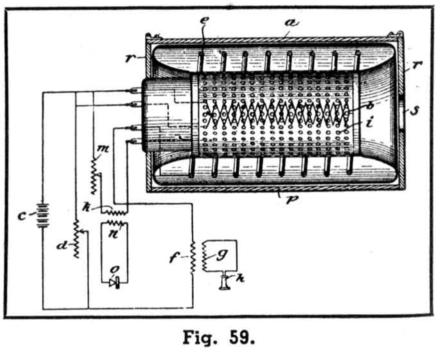

Fig. 59.

to Tigerstedt in 1917.[161] The invention was described as "a relay for undulatory currents comprising an airtight evacuated container, an anode mounted therein, a perforated auxiliary electrode arranged inside said anode, a cathode arranged inside said auxiliary electrode and adapted to be heated by an electric current, and a *mantle* consisting of a magnetically and electrically conducting substance surrounding said container."

Figure 59, which is reproduced from this U. S. Patent, shows the Tigerstedt tube in a circuit arranged for telephone amplification. The spiral wire *"e"* is the anode, the perforated cylinder *"i"* is the grid, and the zig-zag element *"b"* is the cathode. The effect of the external electrostatic and electromagnetic influences was said to be reduced by the concentric element structure, and by the enclosing "mantle." This is the first instance the author has been able to find of the use of a shield on the tube itself.

The other activity was that of Quirino Majorana of Rome, who devised a modification of the de Forest Audion, which he described as an "Electronic Deviator." He obtained a German patent (D.R.P. No. 281014)[162] on this device, which he described in a note to the Accademia dei Lincei in 1912.[163]

The Majorana Electronic Deviator is shown in Figure 60. It is similar in construction and dimensions to the de Forest Audion, except for the grid. The de Forest grid was replaced by two comb-shaped electrodes with their prongs alternating in the same plane. This was the first use of co-planar grids, as far as the author has been able to determine, and we do not find it again for twenty years. Majorana's device was intended for use as a wireless detector, but its possible use as a telephone relay was suggested by Max Ikle.[164]

While we are concerned only with factual material on the evolution of the vacuum tube, at this point an observation might be made, in passing, on the difference between the approach to the work done in America, and the approach to the work done abroad during this period.

The inventors in America, de Forest and his associates, struggling to make and use vacuum tubes, did not actually understand the theory of such devices. They were trying out gadgets to solve their problems with wireless, and by the process of elimination were turning out truly remarkable devices which, when perfected by our applied scientists, opened the door to modern communications.

In contrast to this we have seen how abroad the pure scientists had worked for many years on the mechanism of electrical conduction through gases, and had built up a background of vacuum tube information and technique. Then the inventors stepped into the picture, and by adapting certain laboratory techniques, produced a cathode-ray type of amplifier tube. This line of development eventually produced not only a telephone amplifier, but the cathode-ray tube so essential to the television of today.

We have also seen how confused was the picture, both in Europe and in

America, on the question of gaseous conduction versus pure electron discharge operation. This condition existed until the accumulated scientific knowledge of electronics was brought to bear directly and to the fullest extent on the practical problems of the utilization of these inventive advances.

With the work reported in this and previous articles, evolution of the

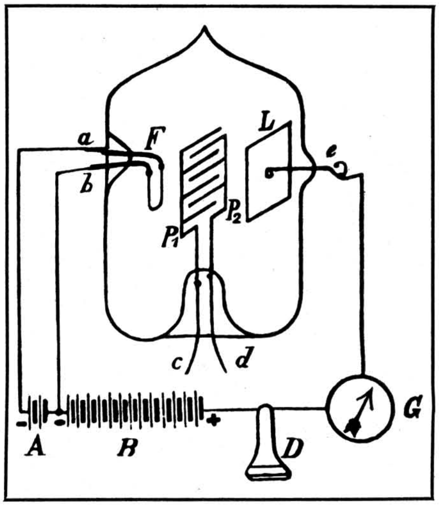

Fig. 60.

vacuum tube advanced from the invention stage to that of industrial development. In the succeeding article we shall show how this development progressed in the largest communication laboratory in America, that of the Bell System.

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Captions for Illustrations

Figure 49. Von Lieben high vacuum cathode ray relay of 1906, using magnetic field for beam defocussing. Reproduced from *D.R.P.* Nr. 179807.

Figure 50. Dieckmann and Glage cathode ray relay of 1906, using magnetic deflection of cathode rays. Reproduced from *D.R.P.* Nr. 184710.

Figure 51. Von Lieben gaseous cathode ray relay of 1910, using magnetic deflection of cathode rays acting as "ionizer." Reproduced from *D.R.P.* Nr. 236716.

Figure 52. Von Lieben gaseous cathode ray relay of 1910, using electrostatic control of cathode rays. Reproduced from *D.R.P.* Nr. 249142.

Figure 53. Photograph of Von Lieben gaseous cathode ray relay made in 1911. Reproduced from *Archiv fur Geschichte der Mathematik,* 1931.

Figure 54. Von Bronk arrangement for using the de Forest Audion as a high frequency amplifier. Reproduced from *D.R.P.* Nr. 271059.

Figure 55. Von Lieben mercury vapor repeater tube in final form. Reproduced from *D.R.P.* Nr. 264554.

Figure 56. Large size LRS Repeater, with perforated sheet aluminum grid and pin type base. Photograph courtesy *Bell Telephone Laboratories.*

Figure 57. LRS Repeater with cylindrical base. Reproduced from *Archiv fur Geschichte der Mathematik,* 1931.

Figure 58. Temperature regulator for LRS Repeater. Reproduced from *D.R.P.* Nr. 293460.

Figure 59. Tigerstedt telephone relay arrangement using magnetically shielded and concentric electrode structure. Reproduced from *U.S.P.* 1,212,163.

Figure 60. Majorana's Electronic Deviator. Reproduced from *Jahrbuch der drahtlosen Telegraphie und Telephonie,* 1913.

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Oscilloscope Applications

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In addition to providing hitherto unobtained speed, the oscillographic method of obtaining tube characteristics permits, at the same time, the use of higher electrode voltages than would be possible in taking such data by other means. This is because the various instantaneous values of voltage are maintained for too short a time to produce any injurious effects upon the electrodes. A peak value of plate voltage may thus attain a value which, under conditions of observation, by means of meters, would result in certain damage to the tested tube.

In testing tubes, *any* current characteristic may be plotted on the oscilloscope screen by employing the voltage drop produced by the current flowing through a small resistance. Rectifiers and other diodes may be tested as well as multielectrode types.

Indication of Gas Engine Cylinder Pressure

In investigations of internal-combustion engine operation, cylinder pressures can be measured by means of pressure gages similar to the familiar steam gages. This system possesses numerous limitations. Recent methods make use of electromechanical-pressure kickup devices which are fastened to the outside of cylinder walls and record internal pressure during the various cycles of engine operation. This apparatus is susceptible to great vibrations of the motor and does not possess the required sensitivity for investigating action of anti-knock gasolines.

Engine cylinder pressure is recorded in modern motor laboratories by means of radionic equipment which employs the oscilloscope as an indicator. In this system, virbrational impulses are transmitted from the *inner* wall of the cylinder by a light beam.