ELECTRON TUBE DEVELOPMENT AND ITS PLACE IN THE PROGRESS OF RADIO ART

by

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Introduction.

A complete survey of the development of the electron tube as generator of radio frequency power would make too great a volume. In this brief review, only the high points of this remarkable development, also of its bearings upon the progress of the entire radio art will be touched upon, as the author saw it throughout his life.

Early period.

It has become common place to say that the invention of Radio fifty years ago was one of the greatest events in the life of civilized humanity. Many of its implications are well known to us and, surely, many are yet to come. Without exaggeration one may say that radio shrank our earth and that it may yet shrink our planetary system.

Looking retrospectively at the wonderful achievements of Radio art, one may ascertain that, among the individual factors which contributed to its advancement, during the fifty years of its existence, the invention of the grid-controlled electron tube was undoubtedly the most outstanding. If, further, one wishes to evaluate the relative importance of the "receiving" versus "transmitting" variety of the electron tube, unquestionably the latter *par excellence* helped to open new vistas in radio. Indeed, radio telephony, radio broadcasting, short wave round-the-earth communications, television, radar and other micro-wave applications became possible only because the electron tube came to replace the earlier types of generators of high-frequency power. The role of the receiving tube was always that of quantitative improvement of various functions of radio systems, through tremendous increase of their overall sensitivity and refinement of performance.

Here, it may be remarked that the common division of radio tubes into "receiving" and "transmitting" classes with better logic can be replaced by "small signal" and "power output" high vacuum tubes. The latter names more closely describe the essential functional difference between the general class of linear amplifiers and detectors, in which the distortionless reproducing of signals is of paramount importance, and the class of power amplifiers and oscillators, in which power output is the main purpose. It is important that this classification is not limited by the physical size of the tube.

It is known that the electron tube, with internal control of radio frequency currents, was proposed (about 1907–1908) by at least two independent inventors, – one, the "Audion" by Lee De Forest in the U. S. A.,(1) and the other the *cathode relay* by von Lieben in Austria.(2) In the latter case, it was initially a magnetically controlled electron beam tube with two anodes; then, also the grid controlled "cathode relay" with a grid was proposed by the same inventor. The first tubes were originally intended, mainly, if not only, for detecting radio waves. However, in this capacity the electron tube had to compete with other available detectors, especially with the crystal or contact detector (frequently called at that time, the thermo-detector). Indeed, in spite of their greater sensitivity, the new electron tube detectors required bulky auxiliary batteries for heating the cathode and for supplying voltage to the anode; expecially objectionable was this for applications in mobile apparatus. In fact, the electron tube was employed with better success in those early days in long telegraph and telephone lines as a *repeater* (Bell Telephone Co. in U. S.), or *cathode relay* (Telefunken in Germany). Experiments in this direction were conducted

(1) LEE DE FOREST, *Space telegraphy*, United States Patent 879,532, January 1907–February 1908.

(2) V. R. VON LIEBEN, German Patent No. 179,807, March 1906; V. R. von LIEBEN, R. REIZS and S. STRAUSS, German Patent No. 236,716, September 1910.

between 1910 and 1915 and, since, applied practically in long distance wire communication.

In the radio field the electron tube attracted more attention from the radio designers only when it became known that, in addition to its detecting and amplifying properties, the grid controlled tube could be made to generate CW oscillations of any desired frequency, up to the highest employed in radio. This discovery resulted in designing radio-telephone transmitters by far more flexible and efficient than all previous systems, such as Poulsen arc, high frequency alternators and super-audio spark-gap transmitters.

Two factors slowed down initially the development of radio telephony. First, poor vacuum technics made individual tubes capable of withstanding only relatively low plate voltages, hence, of generating relatively very low outputs; moreover, because of imperfect manufacturing, tube operation was far from being stable and uniform. Second, beside military and navigational applications over very short distances in competition with code transmission already in existence, there was no urgent practical demand for radio telephony; in fact, it was viewed rather as an amusing innovation which only the enthusiastic pioneers tried to force into practice. Indeed, the contemporary technical literature witnesses that, up to 1920, – that is more than a decade after the appearance of the three electrode tube – the greatest authorities in the radio field did not visualize real commercial needs for radio telephony except for eventual bridging-over inaccessible terrains in outlying countries where wire or cable lines would not be feasible; or for long range communication, transoceanic or transcontinental, where radio telephony, possibly could compete economically with the telegraph and cable lines.

The beginning of water-cooled tubes.

In November, 1920, Frank Conrad and H. P. Davis of the Westinghouse Company, East Pittsburgh, Pa., conceived and practically demonstrated the future possibilities of commercial, educational and cultural radio broadcasting. (3) This gave the first impetus to the development of high power electron tubes. Fortunately,

(3) I. E. MOUROMTSEFF, *A Quarter Century of Electronics*, « Elec. Eng. », Vol. 66, pp. 171–178, February, 1947.

by that time, the recent invention of Gaede's molecular pump and of the efficient novel mercury diffusion-condensation pump by Gaede and Langmuir improved vacuum technics to such a degree that electron tubes for much higher operation voltages could be designed and manufactured than was feasible with the original "receiving" tubes. In fact, tubes with 50 and a few hundred watt outputs were in existence before the advent of Broadcasting; now an immediate demand for outputs measured in kilowatts was made.

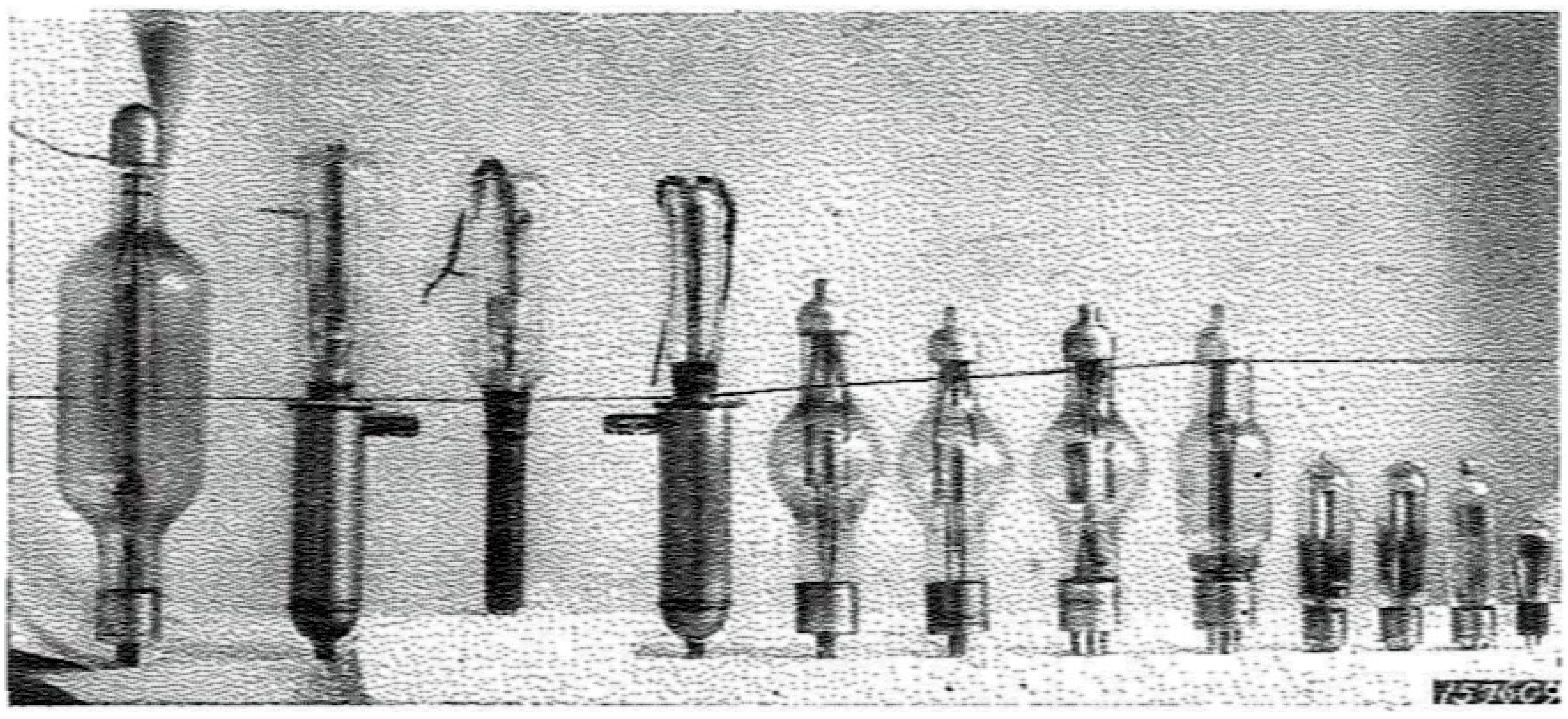

Fig. 1. – Several types of power output tubes in the early days of broadcasting. From left to right are shown: a 5-watt tube; a 50-watt tube with pure tungsten cathode; two 50-watt tubes with thoriated cathodes; a 250-watt with thoriated tungsten cathode; a 250-watt tube with pure tungsten cathode and diamond-shaped anode; two high vacuum rectifiers with pure tungsten filaments, one with diamond shaped, another with flat anode; a water-cooled high-vacuum rectifier; early 10 kW water-cooled triodes with and without water-jacket; a high-vacuum radiation-cooled rectifier.

Everyone realized that the solution of this problem was possible only by designing tubes with water-cooled anodes, presumably with an external tubular metal anode forming a portion of the external vacuum-tight envelope between metal and glass, which would withstand temperature variation up to 400° or 500 °C, without developing cracks. This was an entirely new demand on glass technics. Several solutions were proposed and attempted all over the world. However, the problem was not solved satisfactorily until Housekeeper of the Bell Telephone Laboratories, U. S., proposed his method (1922). It consisted in machining the open end of a cylindrical copper anode to form a tapered portion with a knife edge of a few hundredths of a millimeter. When heated to a temperature close to the melting point of glass, copper and glass react chemically, and, under a slight pressure of the glass blower's paddle, they generally form an excellent bond. Subsequent cooling to room temperature and repeated heating and cooling in the exhaust oven does not put excessive strain on the glass of the seal, because during thermal expansion and contraction the thin copper wall yields.

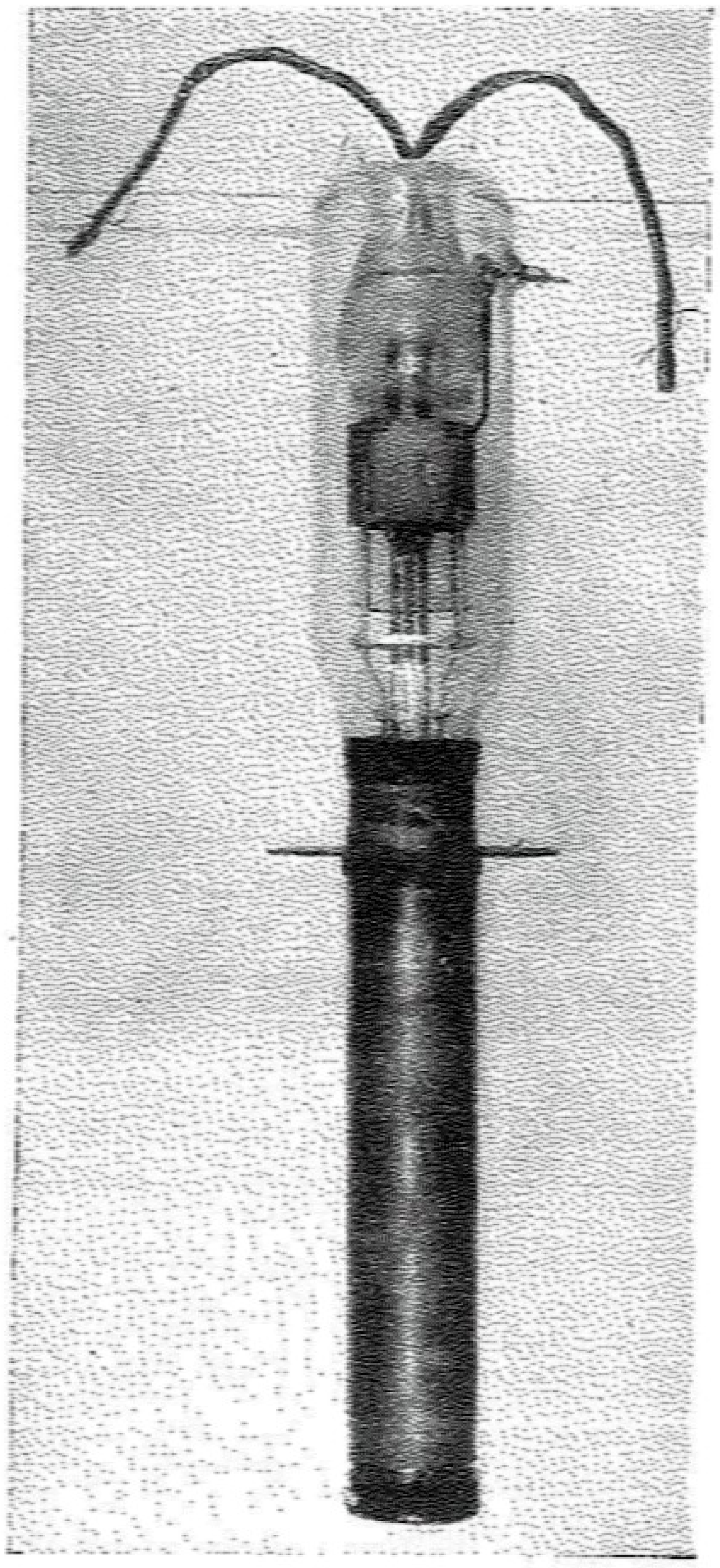

Fig. 2. – An early 10 kW water-cooled tube. The anode is made of a piece of ordinary copper tubing with the outer end closed by a glass window. The grid seal is of a primitive « pinch » type limiting tube operation to rather low frequencies (one or two megacycles).

The solution of the problem of the copper-to-glass seal resulted in immediate designing of water-cooled tubes with 10 to 20 kW output. Dimensionally they were no larger than 1 or 2 kW all-glass tubes having anodes cooled by heat radiation (Fig. 1). One of the very first tubes of the new type, with a 1-½ inch copper anode having the "outer" end closed by a glass cup, is shown in Fig. 2. The end-window permitted very good centering of the grid and filament structures. This was an important requisite in the time when all assembly work was done by the glass blower's hands. Special glass working lathes were introduced much later. In Fig. 3 another early tube is shown having an enclosed drawn copper anode, also 1–½ inch in diameter, side by side with its modern version. The active or the hot portion is identical in both cases. However, the improved glass technics permitted the use of modern moulded *glass dishes* (Fig. 4) for sealing-in connecting leads and rods which mechanically support tube elements. This renders the whole structure much shorter and more symmetrical. Tubes with glass dishes substituted for the customary flared stems, generally speaking, cost less in production and their rated frequency ceiling can be raised considerably. It took, indeed, two decades

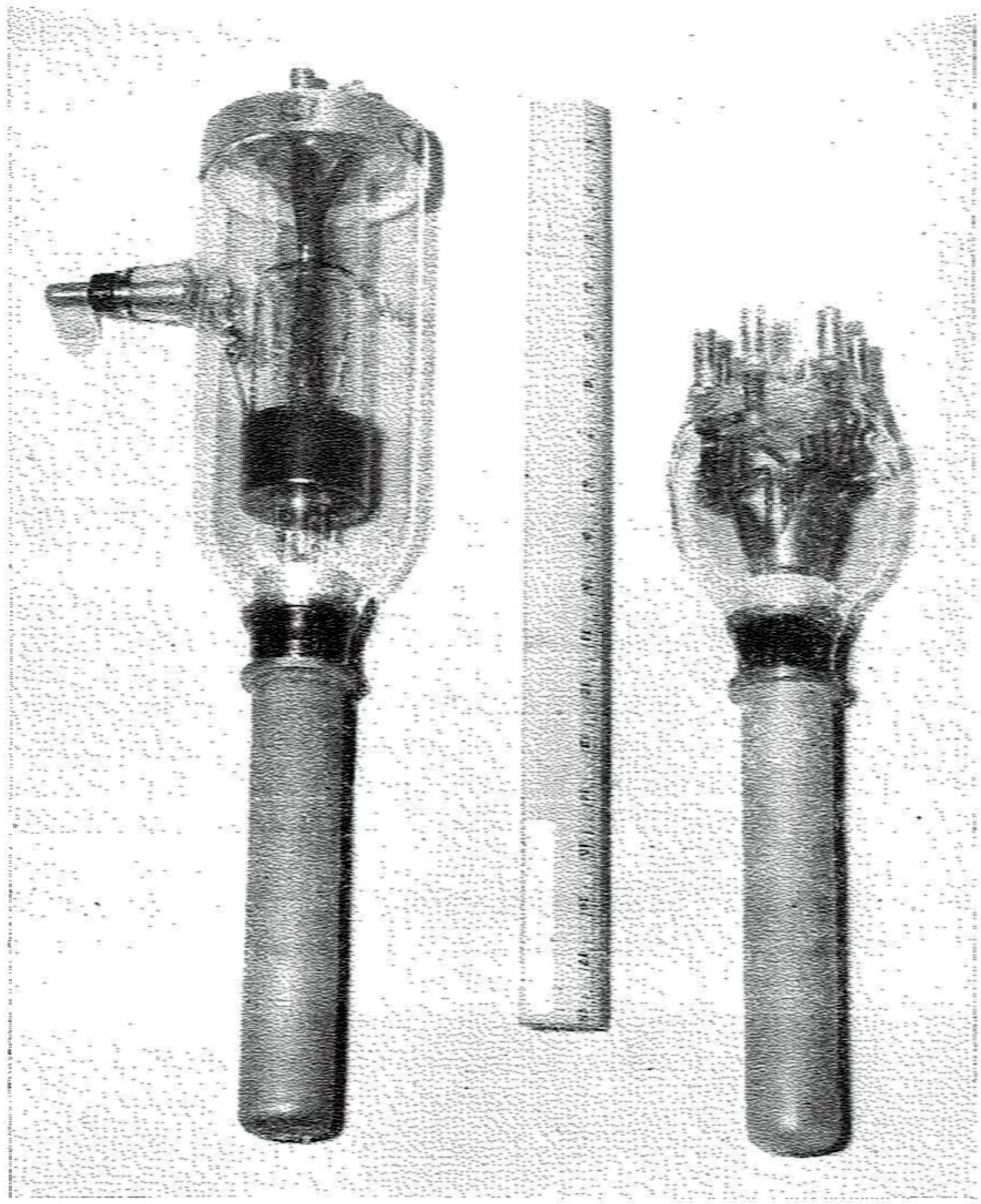

Fig. 3. – An early standard 20 kW water-cooled tube (type 892) and its modern version. Tube elements inside the anode are identical; however, in the first tube the whole structure is supported from a long stem and a flare, while in the second tube a modern moulded glass dish is used.

to arrive at this simple idea and to develop adequate glass technics.

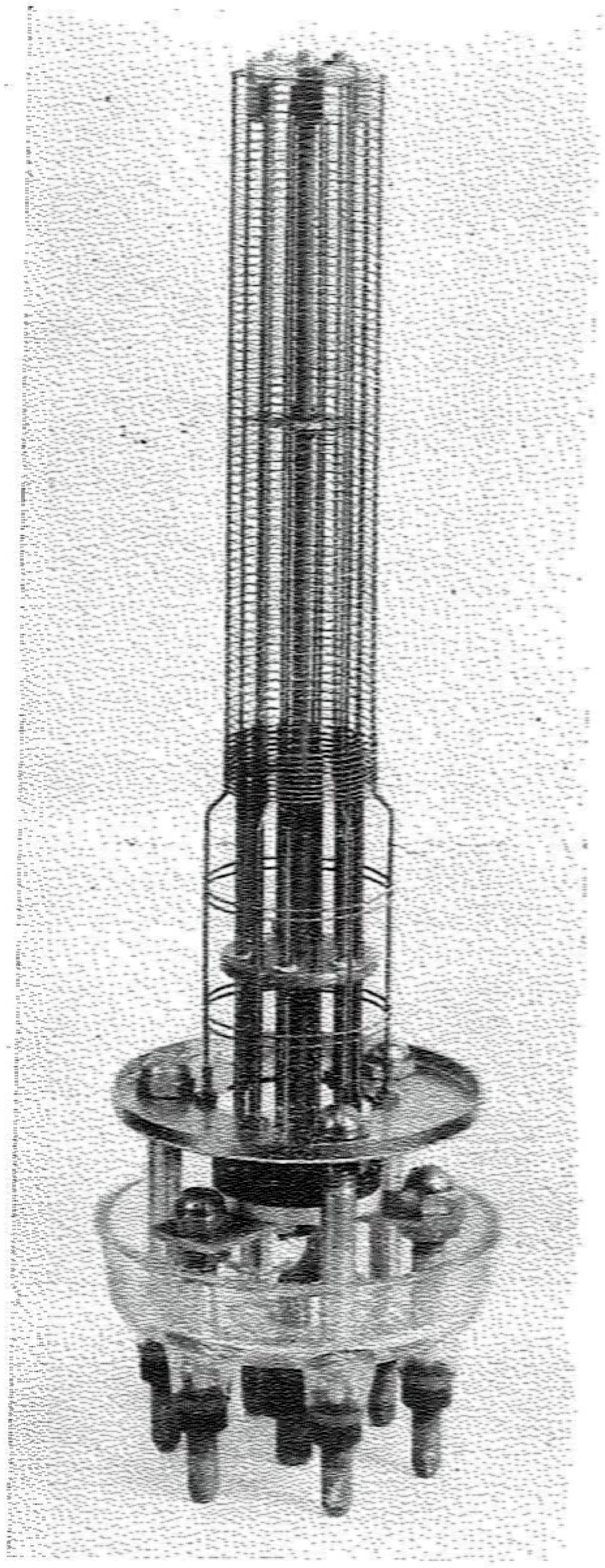

Fig. 4. – Glass dish of a larger tube (895 type) shown with mounted grid and filament consisting of 12 vertical strands.

It should perhaps be mentioned that several tube types with iron alloy anodes were designed in the early days of water-cooled tubes. However, in practice, the designers encountered troubles from unexpected quarters; namely, iron and its alloys which are not completely free from corrosion proved to be *transparent* to hydrogen ions which are formed at the wetted surface of the anode, as a result of electrochemical reactions. With time such tubes becomes "gassy" in service, in spite of all precautions for proper outgassing tube elements during exhaust.

Tubes for short-wave long distance communications.

Looking back through the history of radio communications one may notice an interesting fact. Hertz in his experiments used what we now call micro-waves or ultra-short waves. In practical applications, radio started with "short" waves, – from 20 up to several hundred meters, – as in the early Marconi and other systems. After ten years of existence, radio showed a pronounced trend toward longer and longer waves, especially in long-range communication; this was compatible with the desire to design more powerful transmitters, also it was known to make radio-communication less dependent on the season of the year and on the hour of the day. The long wave trend culminated, in the beginning of the 1920's, in the installation of such transmitters as the one at Rocky Point, Long Island with Alexanderson h-f alternators and with a huge aerial, emitting 16.5 km wave. However, about the same time the great value of *short waves* (below 50 meters) for round-the-earth communication began to be suspected, and by the middle of the 1920's, after systematic studying of wave reflection from the Heaviside layer, it was universally recognized. Then, during the next decade, in the 1930's, the advance of television (and frequency modulation) inaugurated the era of ultra short waves (below 7 meters). Finally, shortly before and during the last war, Radar and many other military applications prompted enormous development of micro-wave devices. Each of the above periods offered new problems to the tube designer, and the full realization of each new application, to a great degree, depended on the early development and adequate design of electron tubes.

No special electron tubes were originally required for short wave applications. Those developed for

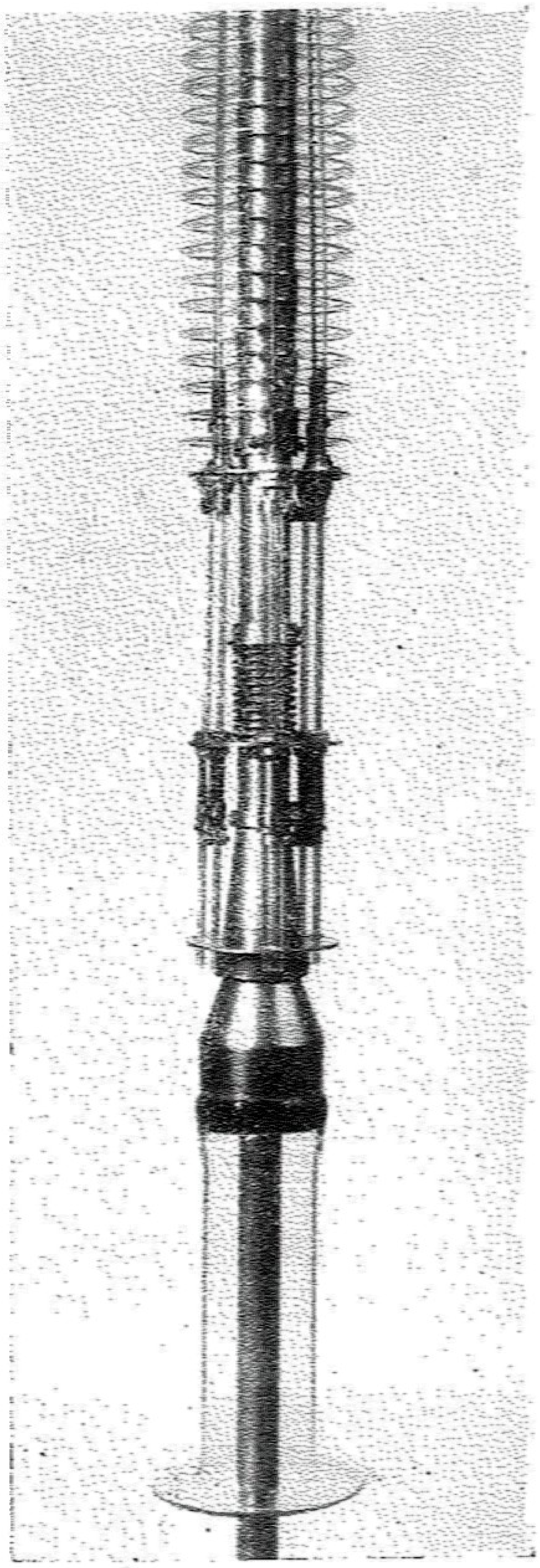

Fig. 5. – A portion of the internal structure of the AW-220 tube. The picture shows a heavy tungsten spring keeping an array of 8 heavy filament strands taut. The spring and the disc grid are cooled by water passing through the tubular central support.

standard broadcast transmitters (above 200 meter waves) proved to be suitable for short wave communication at somewhat reduced ratings. Only some minor changes were necessary in internal tube designs, in order to take care of larger wattless components of h-f currents to the tube elements (compare Figs 2 and 3). On the other hand, the increased frequency of operation made neutralization of internal tube capacitances in operating circuits more critical. As a direct result of this, the *screen grid* tubes and *pentodes* with several hundred watts output found application as power amplifiers. Screen grid tubes of the water-cooled type, though desirable, were not considered by most of the manufacturers commercially justified in those early days, because of design and manufacturing difficulties, mainly with respect to screen grid seals.

About the same time, that is, in the second half of the 1920's, the demand for more powerful broadcast transmitters led to the designing of tubes with larger individual outputs. This was logical, in order to eliminate critical adjustments of a circuit when several smaller tubes were operated in parallel; also fewer tubes in the set reduce the frequency of interrupting the operation for the replacement of deceased tubes. In the U. S., the upper limit for the broadcast transmitters was set by the Government at 50 kW carrier or 200 kW peak output. This fixed the practical upper limit of power output, from an individual tube in push-pull operation, to somewhat above 100 kW. Only a very few types of 100 kW tubes were first designed. The first, among these, the 862 tube was practically the scaled-up design of the popular 207 type of 20 kW size. Another one, the AW–220, for several years used in KDKA broadcast tramsmitter, incorporated some interesting new features, [4] such as a water-cooled grid made of a stack of molybdenum discs; a fluted anode; and a heavy tungsten spring made of 1/8″ rod for taking care of thermal expansion of the array of 8 heavy filament strands 14 inches long. (Fig. 5). Each strand had also an individual tungsten spring for equalization of non-uniform expansion of strands. At present, there are many other types of 100 kW tubes. In Fig. 6 *a* and 6 *b* a more modern 100 kilowatt tube of the 895 type is shown, which is widely used in broadcast transmitters and in industrial heating installations.

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(4) I. E. Mouromtseff, *A new water-cooled power vacuum tube,* « Proc. I. R. E. », Vol. 20, pp. 783–812, May, 1932.

Fig. 6 *a*. – A modern 100 kW tube (WL-895 type) used in several American broadcast transmitters and in many « tin reflowing » industrial installations. The tube is shown soldered into a multi-fin air-cooler, but can be inserted into a water-jacket instead.

Its anode is 4 inches in diameter; its overal length is 24 inches. The early 100 kW tubes, mentioned a few lines above, were about 5 feet long. The difference in length in addition to some other design features is reflected in the operating frequency range: while the recommended maximum frequency for the long tubes was only 2 Mcs, the 895 tube can be used up to 30 Mcs.

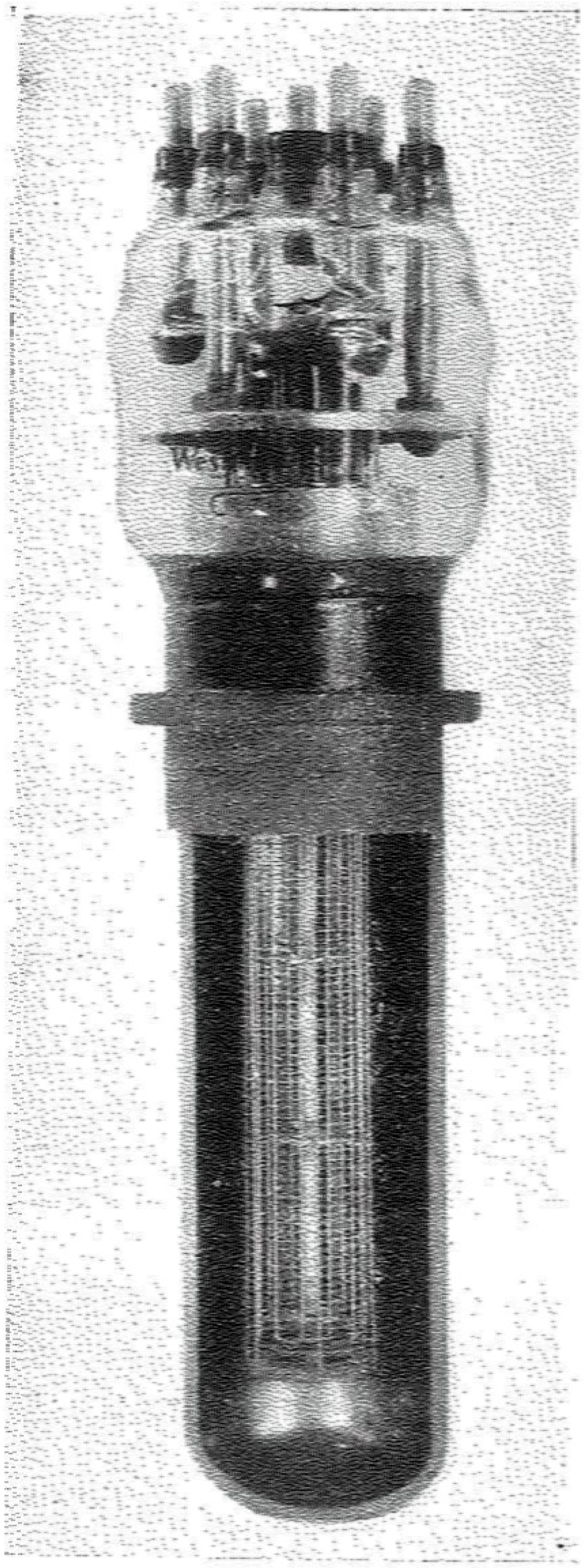

Fig. 6 *b*. – The 895 tube with a portion of the copper anode cut away to reveal the internal structure.

A successful 250 kW tube in U. S. was designed by the Western Electric Company for foreign uses (320A type). Several types of large tubes, with individual outputs of 300 kW or more, were installed in Europe in huge broadcast transmitters. The latter presumably were prompted by political rather than by any other considerations. At the present time, the question of larger tubes is again heard from quarters concerned with high frequency power for industrial heating. Since economic considerations are most important in this case, the question of sealed-off tubes versus tubes continuously exhausted in operation may again arise. In the past, the possibility of the practical use of demountable tubes was occasionally discussed by the American tube manufacturers, [5] but generally speaking, they have never been too enthusiastic about

(5) I. E. MOUROMTSEFF, H. J. DAILEY and L. C. WERNER, *Review of Demountable vs Sealed-off Power Tubes*, « Proc. IRE », pp. 653-664, November, 1944.

this proposition. Just opposite, even with mercury tubes there is, right now, a trend to substitute, whenever possible, the sealed-off for continuously pumped tubes.

Ultra-high frequency tubes.

From the viewpoint of tube development, the decade of the 1930's can truly be called the era of ultra-high frequencies (above 30 Mcs). At the end of the 1920's, it became clear that television was definitely coming. Successful experiments, by Dr. Zworykin in East Pittsburgh, Pa., with reception of television pictures on the cathode ray tube screen (1929), proved its practicability on the receiving end. Later on (1934), Dr. Zworykin and Dr. Farnsworth demonstrated in the U. S. the practicability of the electron beam scanning also on the transmitting end. This was actually visualized, a quarter of a century before, by Prof. Rosing of St. Petersburg, Russia, and Campbell Swinton of England. For a good picture video modulation requires a frequency of about two or three megacycles per second. This implied that the carrier frequency had to be of the order of at least 400 megacycles. No power output tubes for such frequencies existed at that time.

It is known that one of the main limitations of the conventional tubes in operation at such elevated frequencies, comes from their inter-electrode capacitances and the inductances of the long internal leads. Both negligible when a tube is used in a "low" frequency circuit having sizable lump capacitance and inductance, these factors begin to affect tube operation as the frequency goes up; after a certain frequency, the output rapidly drops down to zero. Therefore, a straight-forward designing of an ultra-high frequency tube consisted in "shrinking" the tube. Naturally, power output of such a scaled down tube decreases in proportion to the active electrode area. This is further aggravated by the necessity for reducing the operating voltage with a smaller tube.

Instead of reducing the tube size, another feasible solution was to make the tube an integral part of the oscillating circuit avoiding discontinuities between the tube and the circuit. This principle is commonly recognized now and forms the basis of many important modern micro-wave generators. The first tube designed along these lines, the WL-899 (AW-200 shown in Fig. 7), was designed in

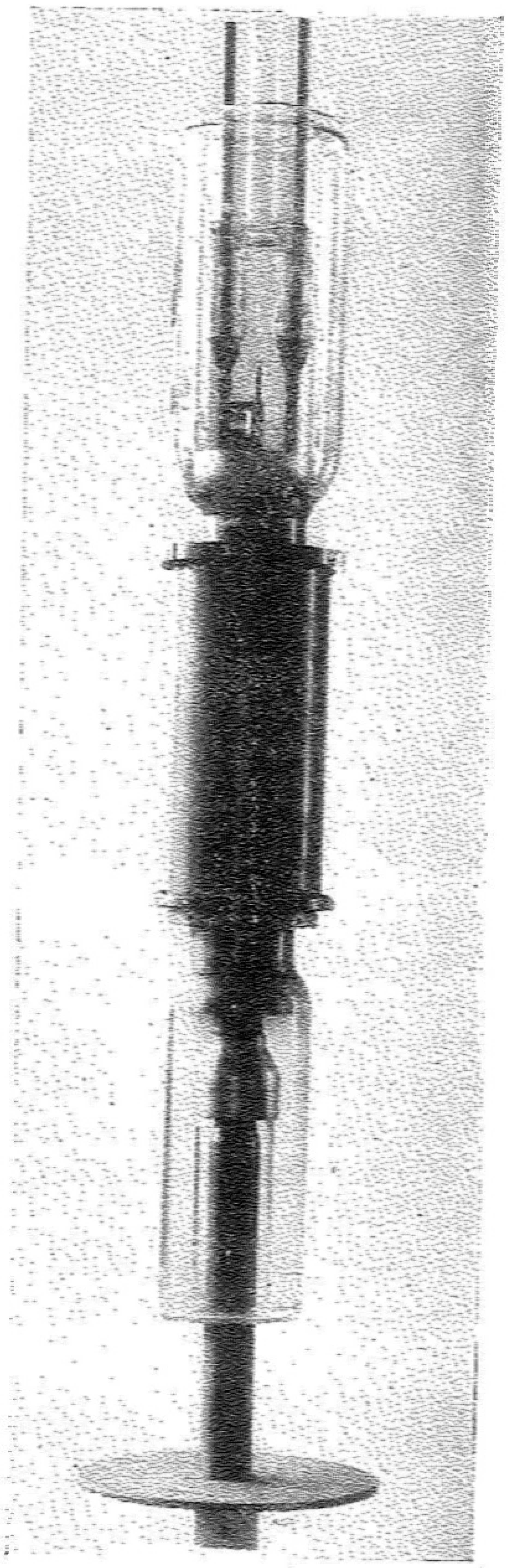

Fig. 7. – An early high-output uhf tube (WL-899 type) used in the first RCA television transmitter on top of the Empire State Building, New York City.

1930. Its concentric anode and grid were made part of a half-wave length concentric transmission line. With the 899 tube, it was possible to obtain 10 or more kilowatts output at 60 megacycles. (6)

The design of the 899 tube is very simple; it is highly symmetrical in the radial direction and has a large axial grid lead of copper tubing; its seal can be effectively cooled by air blast. The grid and the filament are supported from the opposite ends. Originally, the 899 tube was intended for general study of diverse effects in the ultra-high frequency band with high power. Many experiments on dielectric heating – such as desinfestation of grain stored in elevators and of expensive breakfast food in packages, rapid cooking of various kinds of food etc. (7) – have been successfully carried out. However, in view of the high cost of the equipment at the described time (1930–1934), and because of the economic depression, dielectric heating was not adopted by American industry, except in drying tobacco leaves at much lower frequencies which could be produced by standard tubes. The 899 was actually shelved.

In 1935–1936, after the successful RCA experiments with Dr. Zworykin's

(6) I. E. MOUROMTSEFF and H. V. NOBLE, *A new type of ultra-short-wave oscillator*, «Proc. I. R. E.», Vol. 20, pp. 1328–1344.

(7) I. E. MOUROMTSEFF, *Oscillator kills grain weavils in few second*, «Electrical World», Vol. 102, p. 667. November 18, 1933.

new television pick-up tube (the Iconoscope), an ultra-high frequency high-output tube was required. The 899 tube, although not specially designed for television, proved to be the only one available for the purpose; and it was employed in the first RCA experimental 10 kW television transmitter on top of the Empire State Building, New York. The same tube was also successfully used in several early FM transmitters of Major Armstrong, Alpine, N. J., and in the Yankee Network in New England.

The arising commercial demand for high output tubes in u-h frequencies band up to 110 megacycles prompted the designers to look for new solutions. The difficulties were many. In addition to the limitations caused by the tube capacitances and inductances, the electron transit time limitations urged the reduction of the radial distance between the tube elements, expecially between the cathode and the grid. This was contrary to the demand for reduction of the inter-electrode capacitances. Moreover, for the same power output, an ultra-high frequency tube should have a more richly designed cathode with more emission per unit area. This, in its turn, led to increased amount of heat to be taken out through the anode. All these requirements were considered in the 880 tube [(8)] (Fig. 8). The anode with folded-up edge and the filament-grid structure supported from a molded dish are the specific features of this tube. Both of them help to reduce overal length of the tube, hence, its internal capacitances and inductances. The electron transit time in this tube is reduced by making the grid-cathode spacing reasonably small. The tube was rated at 45 kW at 25 Mcs; at 100 Mcs, the ratings are reduced by one half. Yet at sufficiently elevated frequencies, – say about 75 Mcs – even with this design the problem of eliminating feed-back through the triode itself is an estremely difficult one. The power amplifier tends to become a self-oscillator, especially considering the wide frequency band required in video amplifiers.

This last trouble could naturally be solved by replacing the triode by the screen-grid tube structure. However, as mentioned before, with the means of designing and manufacturing available ten years ago, high-output water-cooled tetrodes in 100 Mcs band

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(8) K. C. De Walt, *Three new ultra–high frequency triodes,* «Proc. I. R. E.», Vol. 29, pp. 475–480, September, 1941.

simply could not be justified because of the extreme difficulty of supporting the screen grid and unreasonably high expense.

About the middle of the 1930's, forced air-cooling of copper anode tubes was introduced. The main reason for this innovation

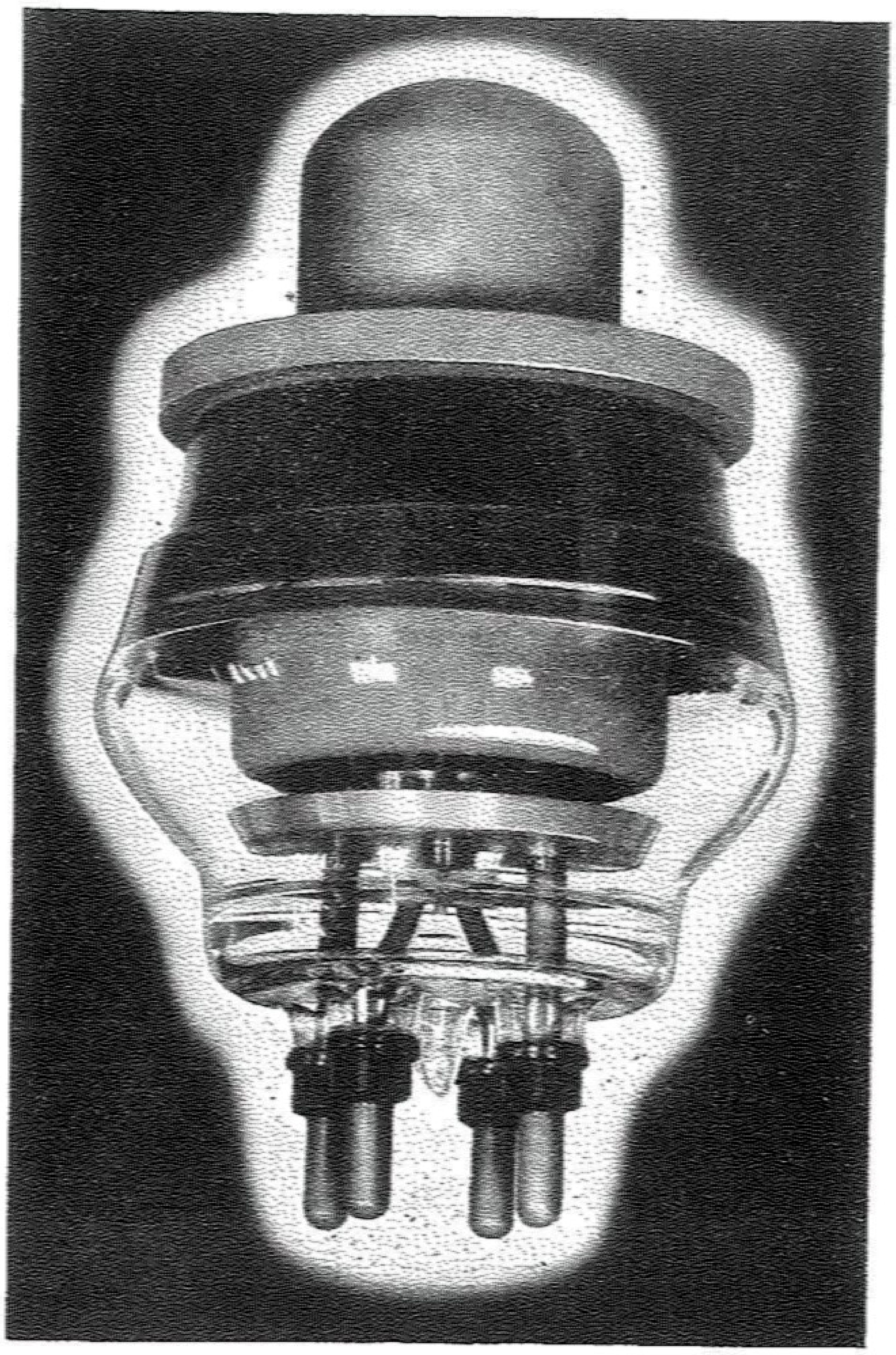

Fig. 8. – One of the early standard uhf water-cooled triodes (type 880) used in television and FM transmitters.

was the necessity, in some cases, of installing power transmitters in unheated rooms, where water could eventually freeze. However, general convenience of dispensing with water systems, especially when water needs purification, increased the popularity of air-cooling on tubes even in the originary broadcast installations (Fig. 7). It is amusing to note that, when air-cooling had been designed by the Westinghouse East Pittsburgh Research Laboratories and offered to the customers at some earlier date (1930), it was unequivocally turned down as impracticable.

Micro–wave generators.

The attemps to circumvent all difficulties, involved in designing tubes of conventional negative-grid triodes or tetrodes

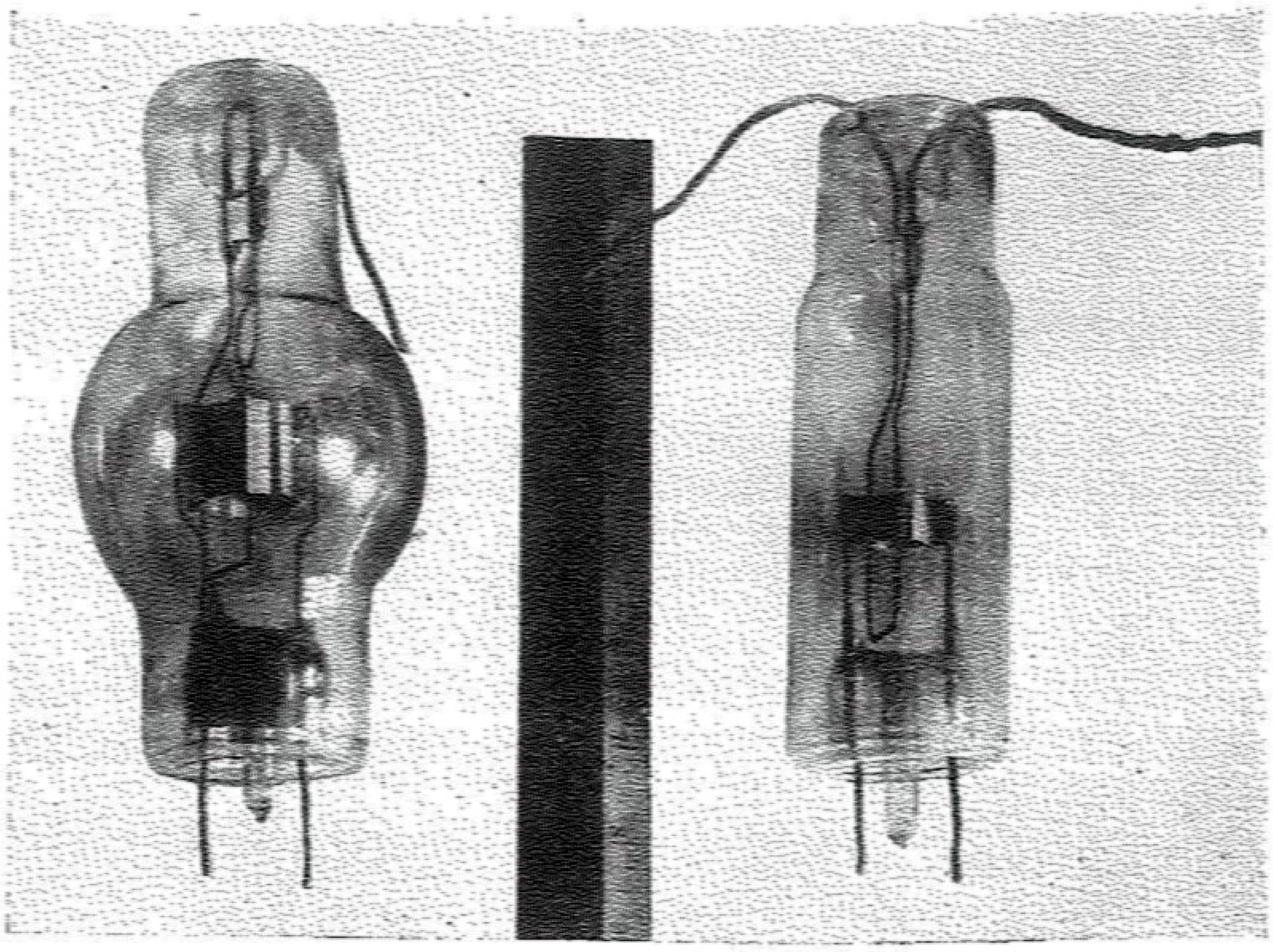

Fig. 9. – Early 30 cm and 10 cm « high output » split-plate magnetrons with 10 and 1 watt output, respectively. Voice and music were transmitted with these tubes using 24 inch parabolic mirrors, in 1931.

for ultra-high frequency operations, early enough directed the thoughts of many experimentors along entirely new channels.

The first historically, and one of the most popular subjects of experimental and theoretical study during some 15 years, was the

Barkhausen oscillator (1920). In this tube, electrons swing back and forth around the grid maintained at a high positive potential, while the plate is negative; thus, in an attached circuit they may produce oscillations of extremely high frequencies (corresponding to decimeter waves). Many attempts were made to develop the Barkhausen oscillator into a practical generator of ultra-high frequency power. However, its extremely low efficiency (about 5 %), the insignificant power output obtainable, (9) and the inherent difficulty of controlling the oscillations excluded, thus far, this type of generators from most practical applications.

Another early and popular generator was the *magnetron*. Originally proposed by Dr. Hull of Schenectady (10) as a single anode, magnetically controlled rectifier, then, as a split-plate magnetron generator of low radiofrequency power (by Habann, Germany), (11) it became the subject of vast laboratory research work after Yagi and Okabe of Japan had discovered (1928) (12) that a split-plate magnetron under certain conditions could become a generator of extremely short waves, down to a few centimeters in length; the power output at these frequencies was originally measured in fractions of a watt. The first magnetron suitable for producing 1 or 2 watts at 10 cm wave was built by Kilgore of the Westinghouse Laboratories at East Pittsburgh. (13) It was discovered that for enhancing useful output, electrons must be permitted, in addition to their normal circular motion, to drift in axial direction (Fig. 9). With this generator, experiments on transmission of voice and music over a distance of about 1 mile by means of parabolic mirrors were demonstrated as early as October, 1931.

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(9) H. N. KOZANOVSKI, *A new circuit for the production of ultra-short-wave oscillations*, « Proc. I. R. E. », Vol. 20, pp. 947–969, June, 1932.

(10) A. W. HULL, *The Magnetron*, « Jour. A. I. E. E. », Vol. 11, pp. 715–723, September, 1921; *The axially controlled magnetron*, « Trans. A. I. E. E. », Vol. 42, pp. 915–920, June, 1923.

(11) E. HABANN, *A new generator tube*, « Zeit. f. Hochfr. », Vol. 24, pp. 115–120 and 135–141, May and June, 1924.

(12) K. OKABI, *Ultra-short waves from magnetrons*, « J. I. E. E. » (Japan), June, 1927.

(13) G. R. KILGORE, *Magnetostatic oscillators for generation of ultra-short waves*, « Proc. I. R. E. », Vol. 20, pp. 1741–1751, November, 1932; *Generation and reception of 9 cm waves*, « Proc. I. R. E », Vol. 22, p. 637, June, 1934.

In 1935, the Heils, husband and wife, published a paper (14) on an electron tube based on an entirely new principle, specially suitable for uhf tubes. The new principle was given by the American scientists the name *velocity modulation*. Somewhat later, but independently, the Varian brothers of Stanford University developed a tube based on a similar principle; their tube

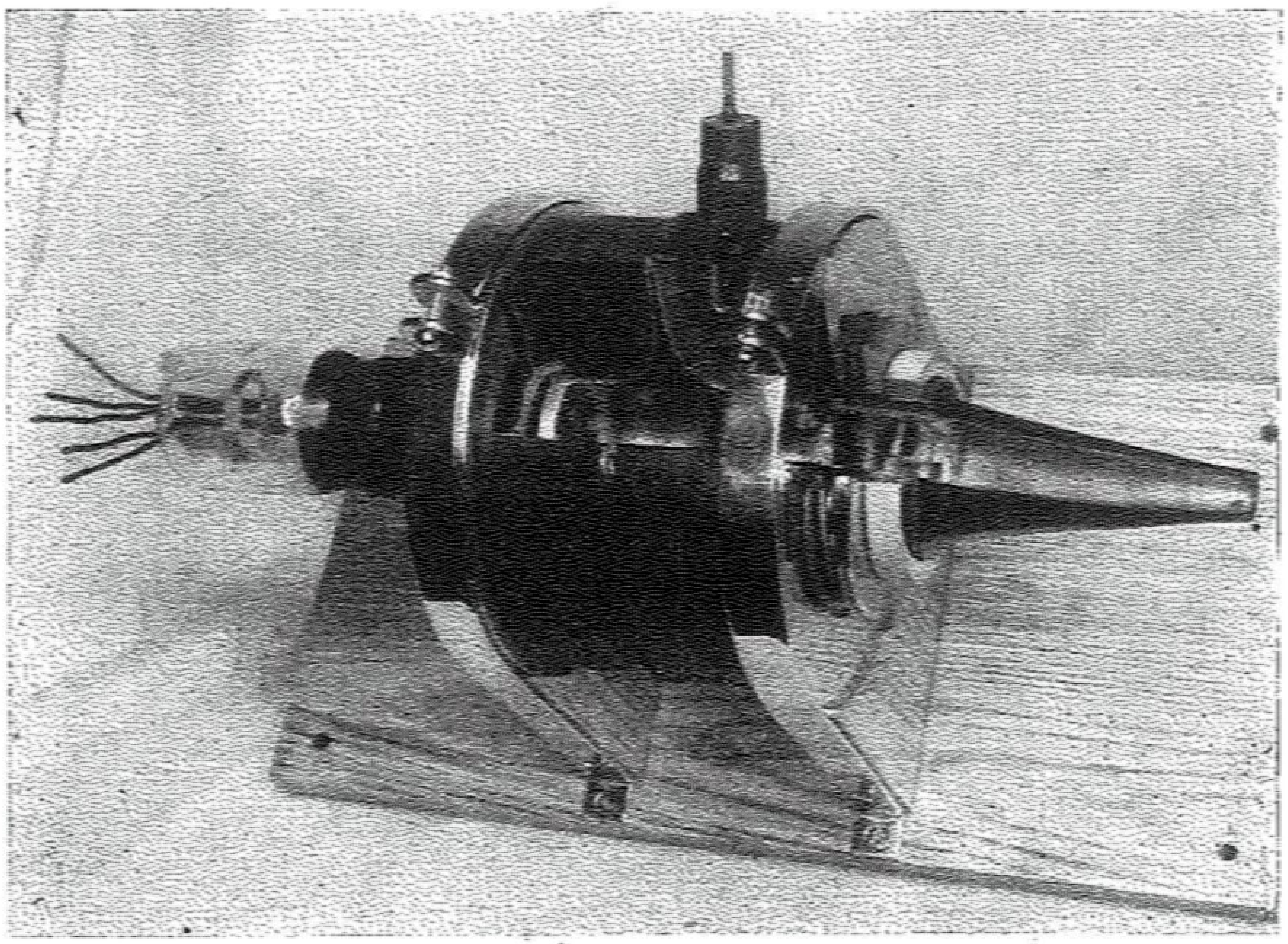

Fig. 10 *a*. - Cut-away view of an early 40 cm Klystron with 150 to 200 watt output. This tube was used in experiments on blind landings in 1940-1941.

received the name *Klystron*. (15) The essential addition to the Heils' idea was the application of cavity resonators as oscillating circuits. Cavity resonators, though known in science for a long

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(14) A. Arseniewa-Heil and O. Heil, *New method of generating short CW waves of high intensity*, « Zeit Phys. », Vol. 95, pp. 752–762, July 1935.

(15) R. H. Varian and S. H. Varian, *A high frequency oscillator and amplifier*, « Jour. Appl. Phys. », Vol. 10, pp. 321–327, May 1939.

time, were just then brought to life by Dr. Hansen of the same University; this feature made the velocity modulation tube especially practicable in the microwave region.

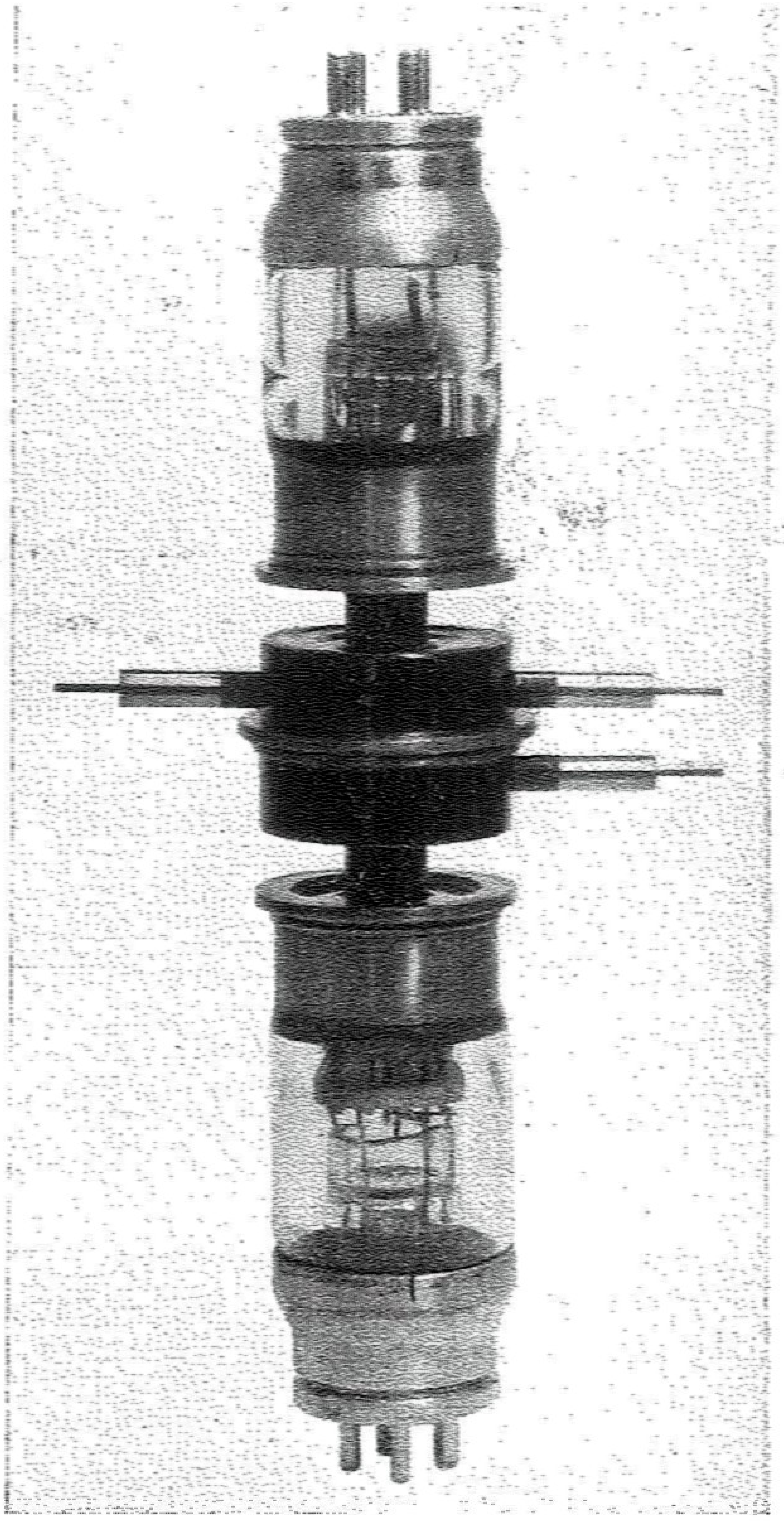

Fig. 10 *b*. – An early 10 cm double cavity Klystron (type 410) with 5 to 10 watt output.

The electron mechanism in a Klystron can in principle be viewed as similar to that of a Barkhausen tube. However, in the Klystron, all phases of the electron mechanism — namely, electron accelerations, velocity modulation, electron bunching, surrender-

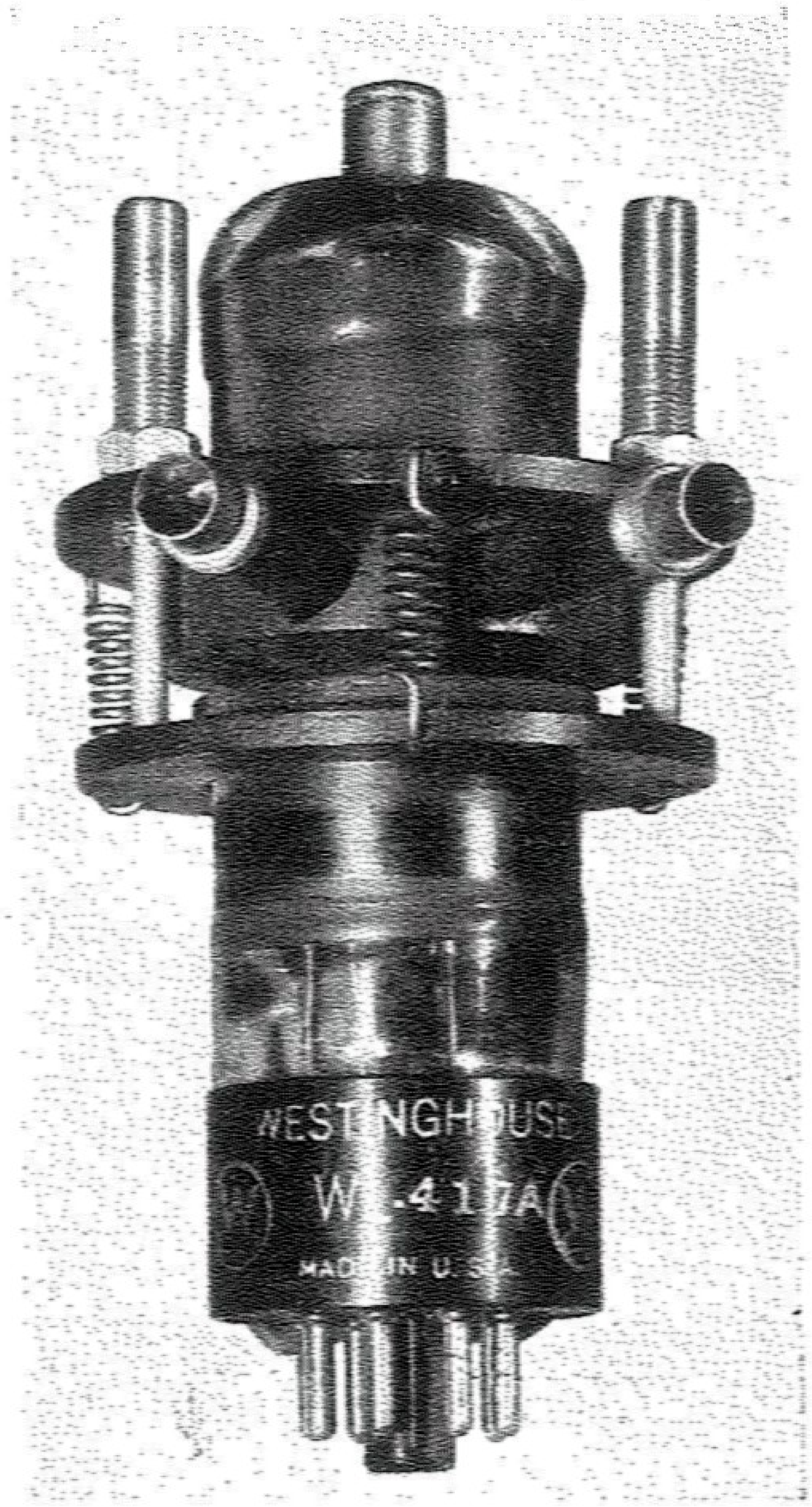

Fig. 11. – Reflex Klystron (WL-417 A type) with approximately 50 milliwatt output.

ing of the energy of the "bunched" electrons to the oscillatory field, and final electron elimination — each is confined to a specially assigned space along the tube axis. In the Barkhausen oscillators, all these functions are not separated in space, but only in time, and therefore may interfere with each other.

The original Klystron, designed for the generator of 10 cm waves, could develop about 10–12 watts output; it had to be operated under continuous pumping. Later on, sealed off models were also developed. An early 40 cm sealed-off model with 150 watts output and a 10 cm model with 10 watt output are shown in Fig. 10. Ten centimeter Klystrons can also be designed for higher outputs, up to several hundred watts. However, as generator of high output frequency power, the Klystron, thus far, could not compete with the multicavity magnetrons. Therefore, only its low power modification, *the Reflex Klystron*, was employed during the war, in the role of the local oscillator in radar receivers and similar other low output circits (Fig. 11).

In a Reflex Klystron, [16] there is only a single cavity resonator; the same gap serves both for modifying the electron velocities and for transfering the energy of the electron bunches to the oscillatory field after their motion has been reversed by a reflector. A Reflex Klystron is simpler to manufacture and to operate; but its normal output amounts to a fraction of a watt. In more recent time, Dr. Wang in the U. S., constructed a Reflex Klystron with a target of a material rich in secondary emission. The output of his tube is considerably greater than in the ordinary Reflex Klystron (up to a few watts).

Tubes for pulse operation.

Early experiments on Radar by the U. S. Navy and Signal Corps reached in 1938 the stage where a practical Radar system could be built. The first equipment, SCR-268, was built around 16 small power-output tubes of the VT-127 A type, giving a total peak output of 75 kilowatts at 205 megacycles. However, because of the strenuous pulse operating condition, the tube life proved to be so short that one had to stop the transmitter for tube replacement every 4 hours. Therefore, the U. S. Signal Corps, decided to have a water-cooled tube with as high output as possible; the goal was at least 25 kW peak output with tube life not less than 20 hours. As a result, the 530 tube shown in Fig. 12 was

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(16) E. L. GINZTON and A. E. HARRISON, « *Reflex–Klystron oscillators* », « Proc. I. R. E. », Vol. 34, pp. 114 P–126 P, March, 1946.

designed by the Westinghouse engineers. Its main features are: a short anode 3 inches in length, 3 inches in diameter, an inverted anode edge, an extremely short grid structure of a large diameter, a simple self-supporting *bird-cage* filament. The latter consisted of 16 thoriated strands, arc welded together at the apex. This was the first example of the application of thoriated filament in a

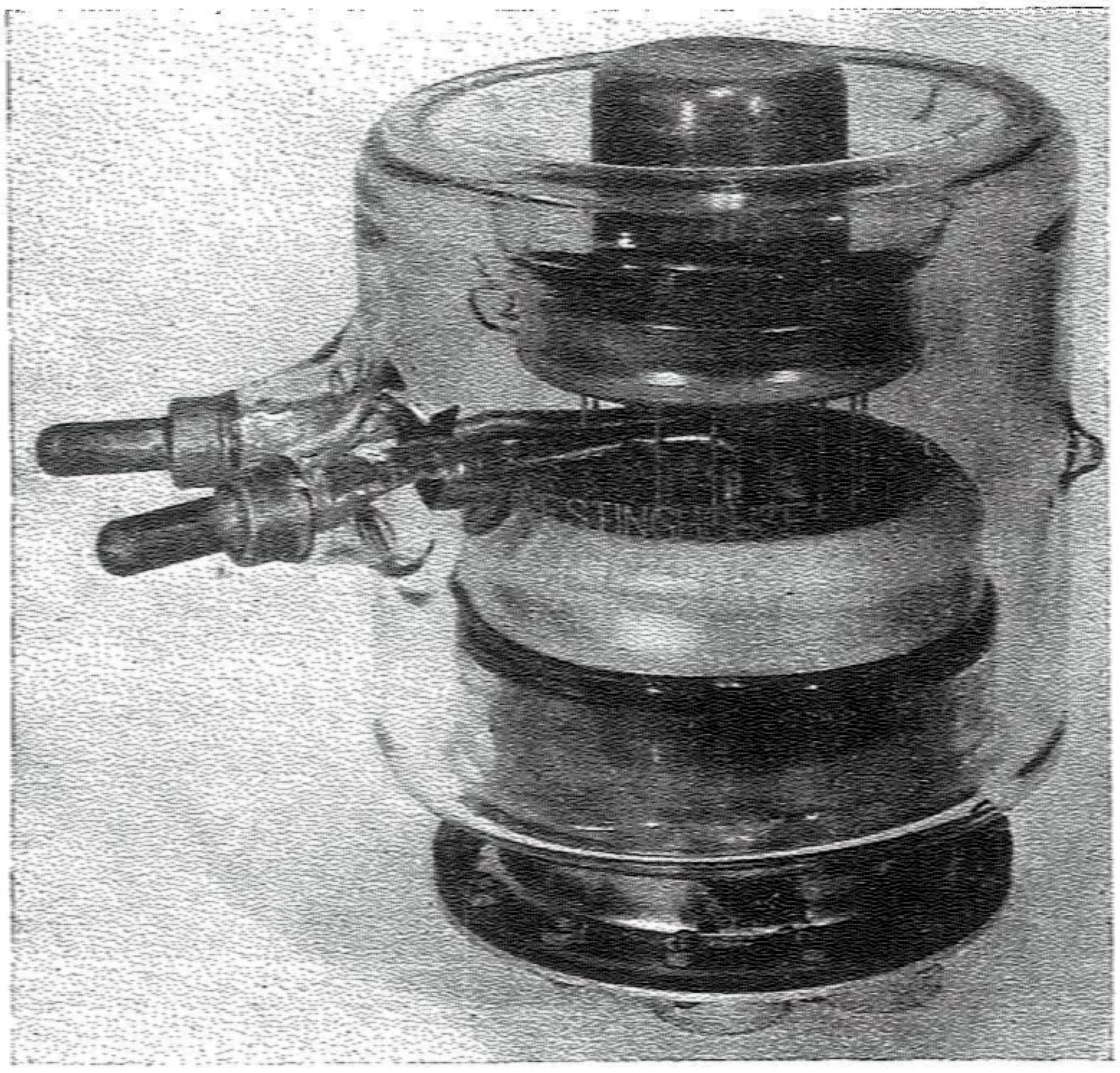

Fig. 12. – First water-cooled tube for pulse-operation (WL-530 type) used by the U. S. Signal Corps in the SCR-270 radar equipment. Ordinary range of detecting airplanes is about 120 miles. Under favorable conditions cost line could be picked up at 1000 miles. Operating frequency – 120 Mcs, peak power output – from 100 to 180 kilowatts.

high-power water-cooled tube. Because of the abundant emission from the cathode (about 100 amperes), the tube could deliver to the antenna in pulse operation up to 180 kW at 120 Mcs. The tube life by far exceeded the designated minimum of 20 hours: it was nearer 3,000 hours. With two tubes in push-pull operation, the

SCR-270 Radar equipment could discover its targets at a distance of 120 miles; however, under favorable conditions this set picked up coast line at 1,000 miles.

Another early pulse-operation tube of an interesting structure

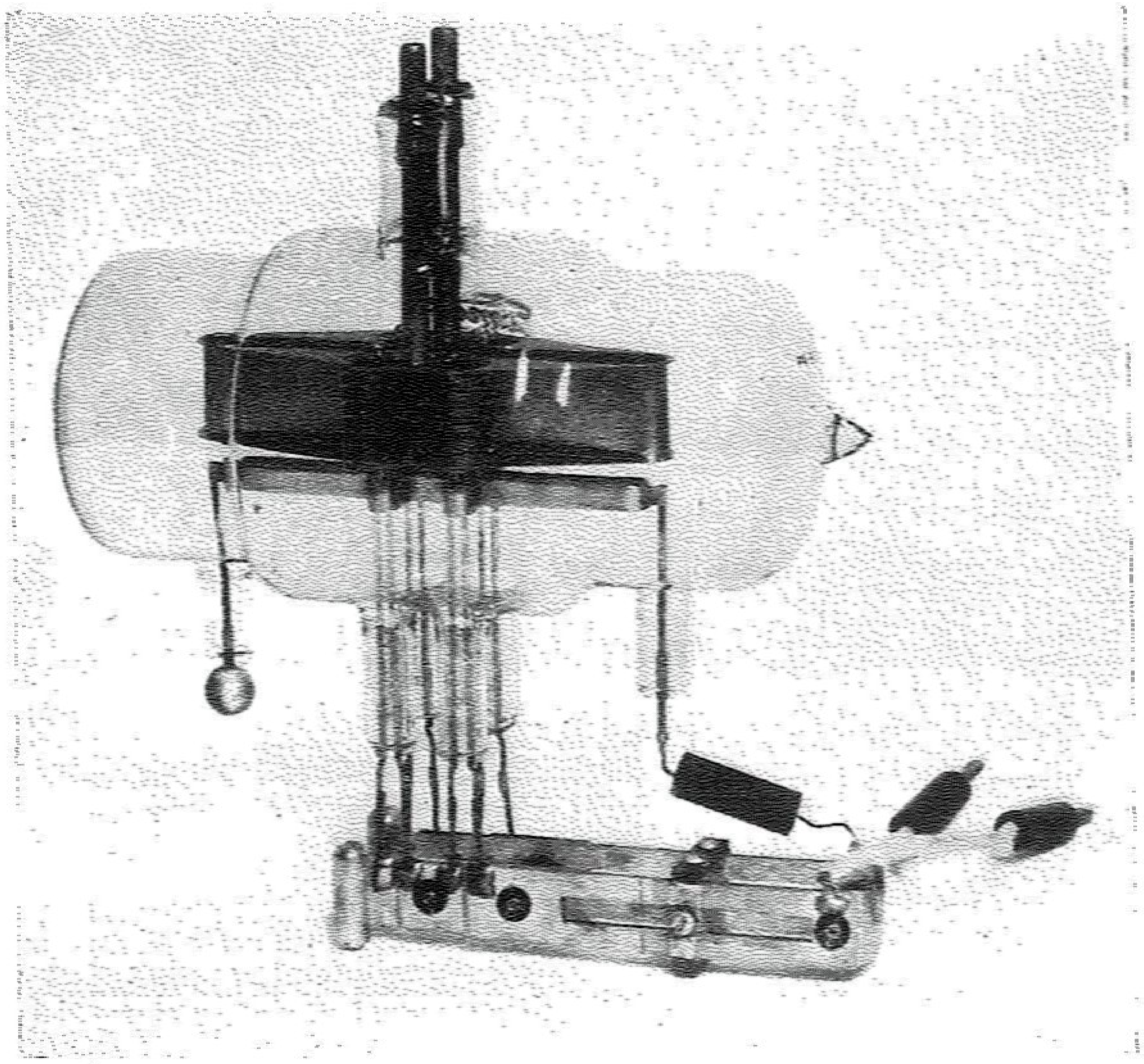

Fig. 13. – A 600 Mcs radar tube designed by Dr. H. Zahl of the U. S. Signal Corps. The tube has four cylindrical triode structures with attached plate and grid transmission line circuits, all in vacuum.

was the VT-158 designed by Major Harold Zahl of the U. S. Signal Corps, for 600 Mcs operation.[17] As Fig. 13 shows, four small cylindrical anode-grid-filament structures with the entire oscillating circuit are built inside a glass bulb. The oscillating circuit comprises

(17) H. A. ZAHL, J. E. GORHAM and G. F. ROUSE, *A vacuum contained push–pull triode transmitter*, « Waves and Electrons », Vol. 1, pp. 66 W–69 W, February 1946.

two symmetrical parallel transmission lines of flat molybdenum bars, one pair connected at the middle to the anodes, another to the grids of the tube.

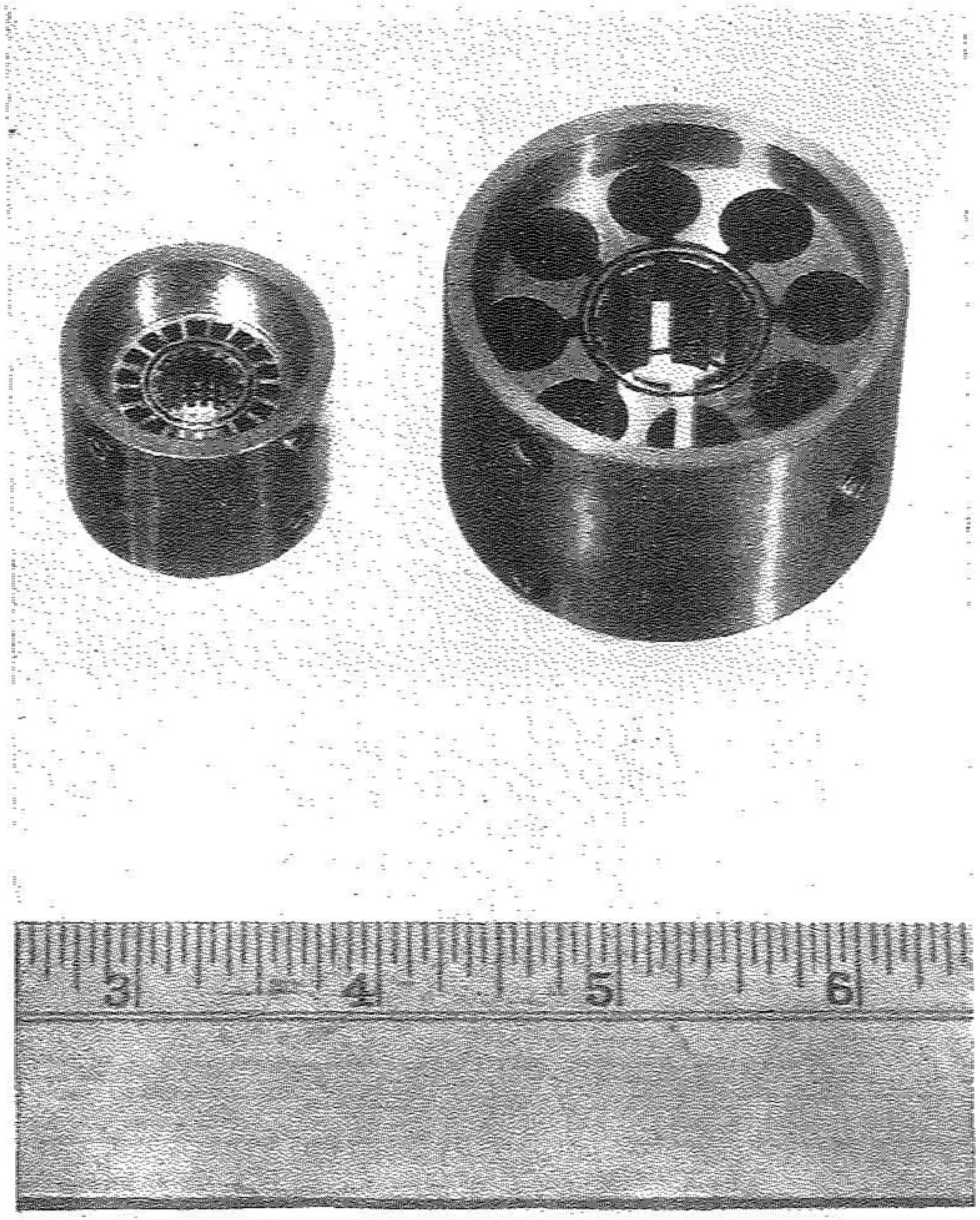

Fig. 14. – Multi-cavity magnetron copper anodes for generating 10 and 3 cm. waves.

A great number of other tubes for pulse operation was developed by the end of the war. As radar technics improved, the duration of individual pulses shrank from 5 or 10 microseconds to a fraction of a microsecond (0.25 microseconds) and the pulse duty to 0.001 %. In these quite peculiar high voltage operating condi-

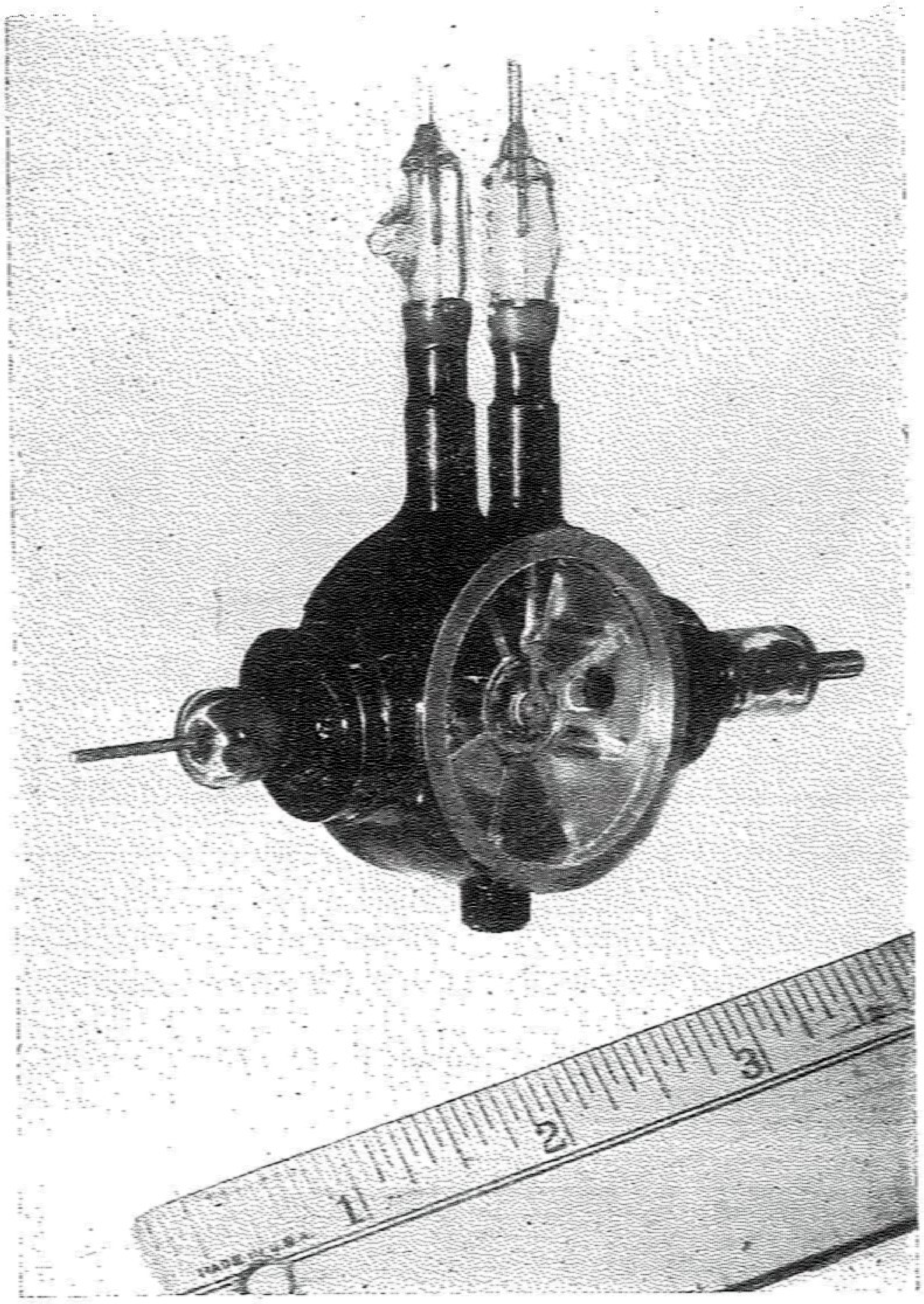

Fig. 15. – An assembled 10 cm magnetron with upper lid removed.

tions, not only thoriated tungsten, but oxide coated cathodes proved to be adequate. It is interesting that the figures of specific emission were quite different from those attainable in conventional CW operation. Thus, with thoriated cathodes, instead of 100 milliamperes per watt of heating power, one could obtain, in pulse operation, almost twice as much, that is, 200 milliamperes per watt. With the oxide coated cathodes, the difference is still more striking; instead of ordinary 0.1 or 0.2 of an ampere per square centimeter of emitting area, a peak emission as high as 10 amperes and more was observed. The probable explanation is that ordinary thermionic emission was augmented in pulse operation by field emission, because of very high operating voltages.

For producing and controlling pulse duration and time interval between two successive pulses, various types of so called modulator tubes were evolved. Some of them were of the three electrode high vacuum tube variety, or of the diode type, and some could be classified as spark-gaps in gas atmosphere.

Undoubtedly, the most interesting among pulse oscillators was the *multicavity magnetron* of several varieties. It was mentioned before that the split plate magnetron became the object of universal study, after the possibility of producing microwave oscillations with this type of tube had been discovered. Volumes of theoretical and experimental work on the magnetron were published during the 1930's; perhaps, no other subject attracted so much attention from the scientists and radio specialists all over the world as the magnetron. A survey of the literature and patents on the magnetron indicates how gradually the idea of a multi-section structure with oscillating circuit inherently built into the tube, was evolved. However, a brilliant solution of the multicavity magnetron is to be credited to Prof. J. T. Randall and a group of British scientists at Birmingham and independently, to Alexeiev and Mailiaroff, two Russian physicists. The new tube was rapidly developed during the war by the joint efforts of the British and American scientists and designers to such a degree that it became the heart of Radar, in combating airplanes and of other important military projects [18] (Fig. 14 and 15).

A multi-cavity magnetron or, as it is also called, the traveling wave magnetron is *par excellence* a microwave generator, for it becomes too bulky, if designed for frequencies below 1,000 Mcs,

(18) J. B. Fisk, H. D. Hagstrum and. P. L. Hartman, *The magnetron as a generator of centimeter waves*, « Bell System Tech. Jour. », Vol. 25, pp. 167–347, April 1946.

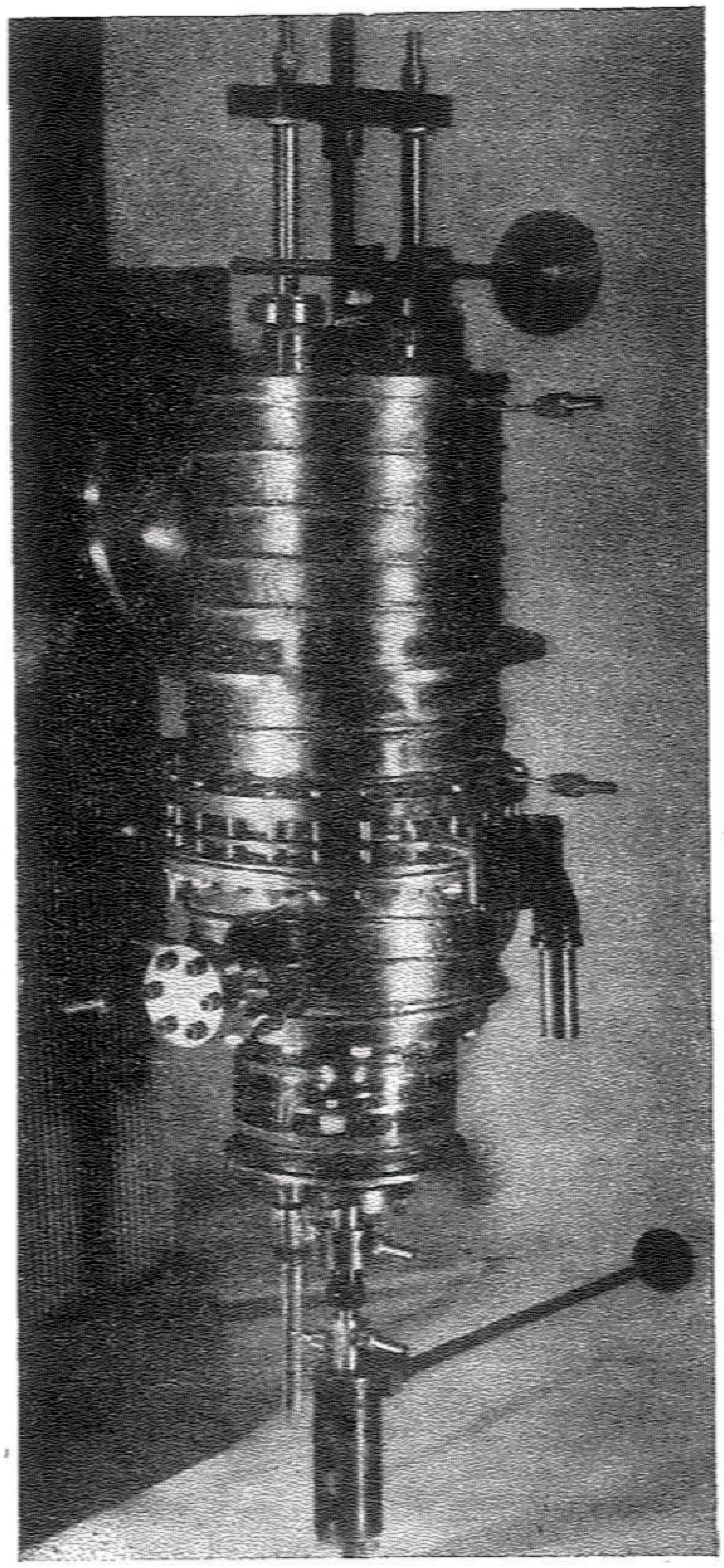

Fig. 16 *a*. – The Resnatron: general view.

while it can be conveniently designed to generate waves of 10 centimeters and down to 1 centimeter. Instantaneous high-frequency power obtained from 10 cm magnetrons in pulse operation. is measured in hundreds and thousands of kilowatts. Operating voltage ranges from 10 up to 30 kilovolts. The necessary magnetic field depends on the frequency and varies from several hundred to several thousand gauss.

Modern tubes for peace time applications.

From the multitude of tubes developed for military purposes, many of them with disregard of the cost, only a few survived

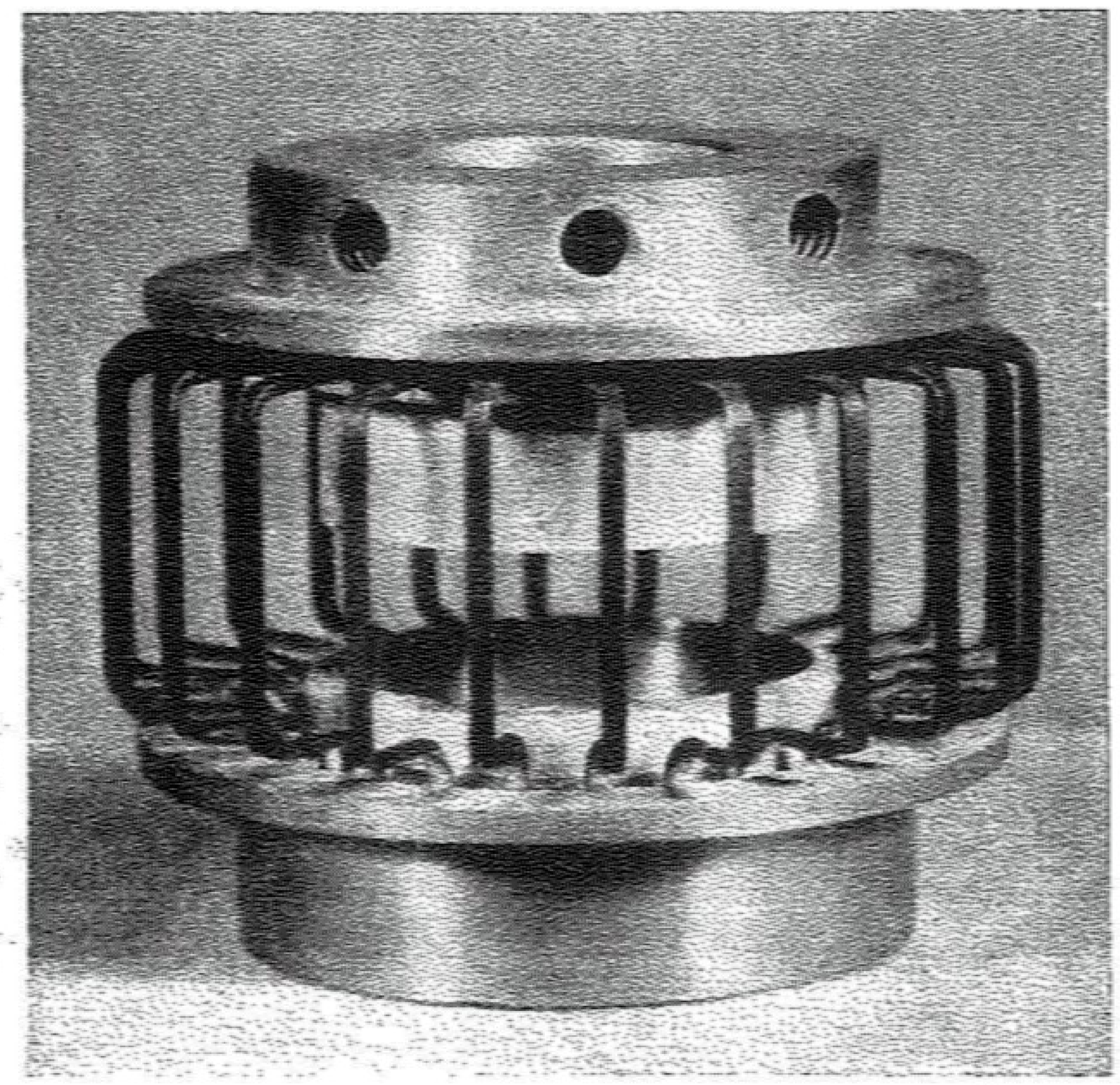

Fig. 16 *b*. – The Resnatron: the cathode.

thus far to find their place in peace time applications. In this section some of the types are touched upon which either are already in use, or may be used with certain adaptations.

The multicavity magnetron will undoubtedly become a universal safety tool in peace time air and sea navigation, perhaps even in automobile traffic control. Commercial considerations may prevent immediate universal use of radar-like installations, but one may be sure that life will prevail upon this inertia, in the same manner as 35 years ago the use of radio was urged in sea navigation after several appalling disasters (S. S. Republic, Titanic and others).

In view of the renewal of general interest after the war toward television and the coming development of its colored variety, new frequency bands will be necessary from 100 Mcs up to perhaps the

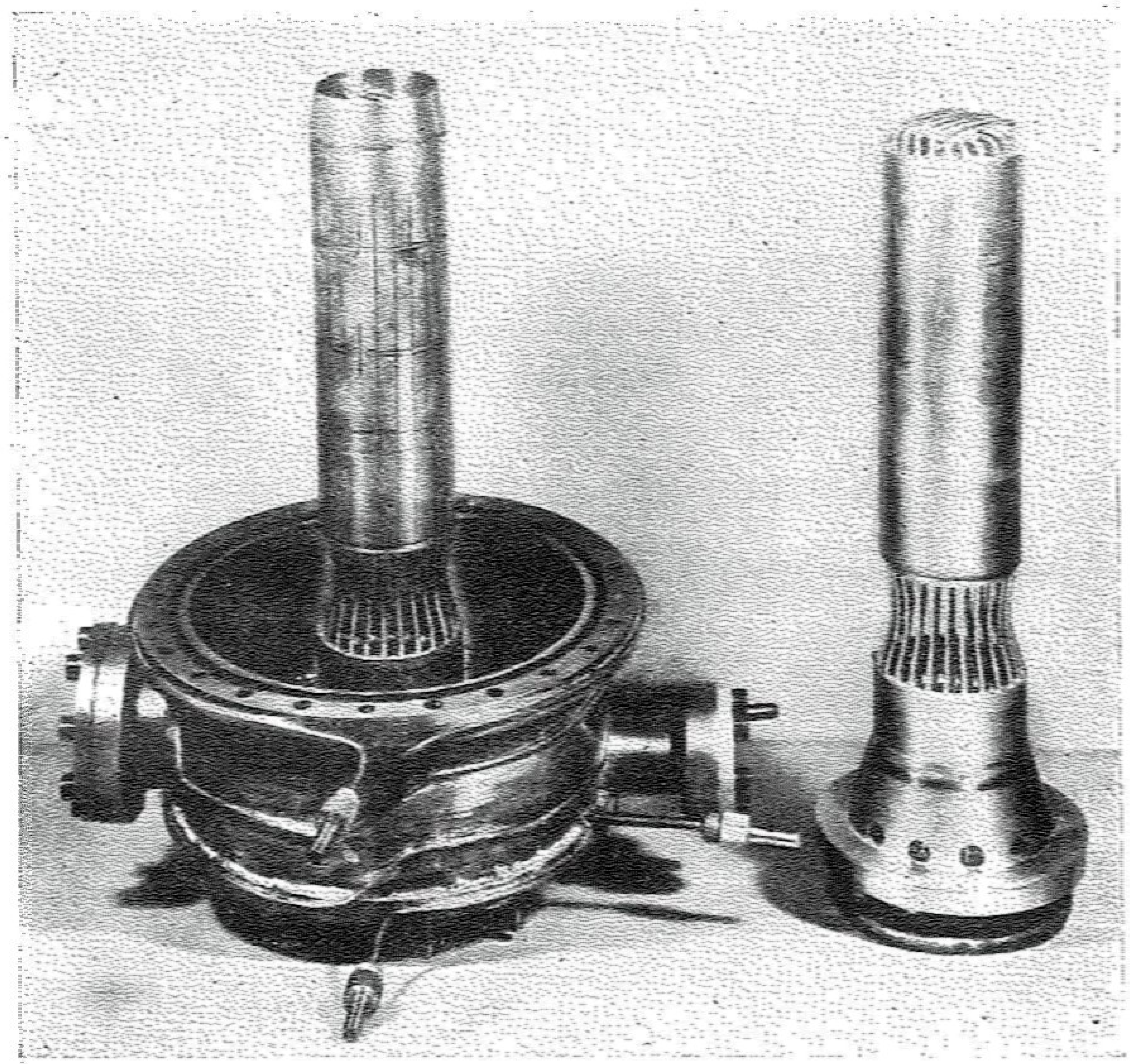

Fig. 16 *c*. – The Resnatron: the screen grid.

microwave region. A few tetrodes with moderate outputs are already available up to 300 Mcs and even for higher frequencies. Since the same tubes can be used in FM, undoubtedly efforts of tube designers will be directed into this channel.

If further extension of frequencies will be required, the multi-cavity magnetrons can be designed for CW microwave operation, with fairly reasonable output of several hundred watts and good efficiency. High output Klystrons may compete with them.

Among the outstanding novel designs, a high power tetrode for frequencies from 300 to 600 Mcs should be mentioned here. This is the so called *Resnatron.* (19) Developed by Dr. D. Sloan and Dr. W. B. Fritter and their co-workers at the Westinghouse Research Laboratories, East Pittsburgh, it was used during the

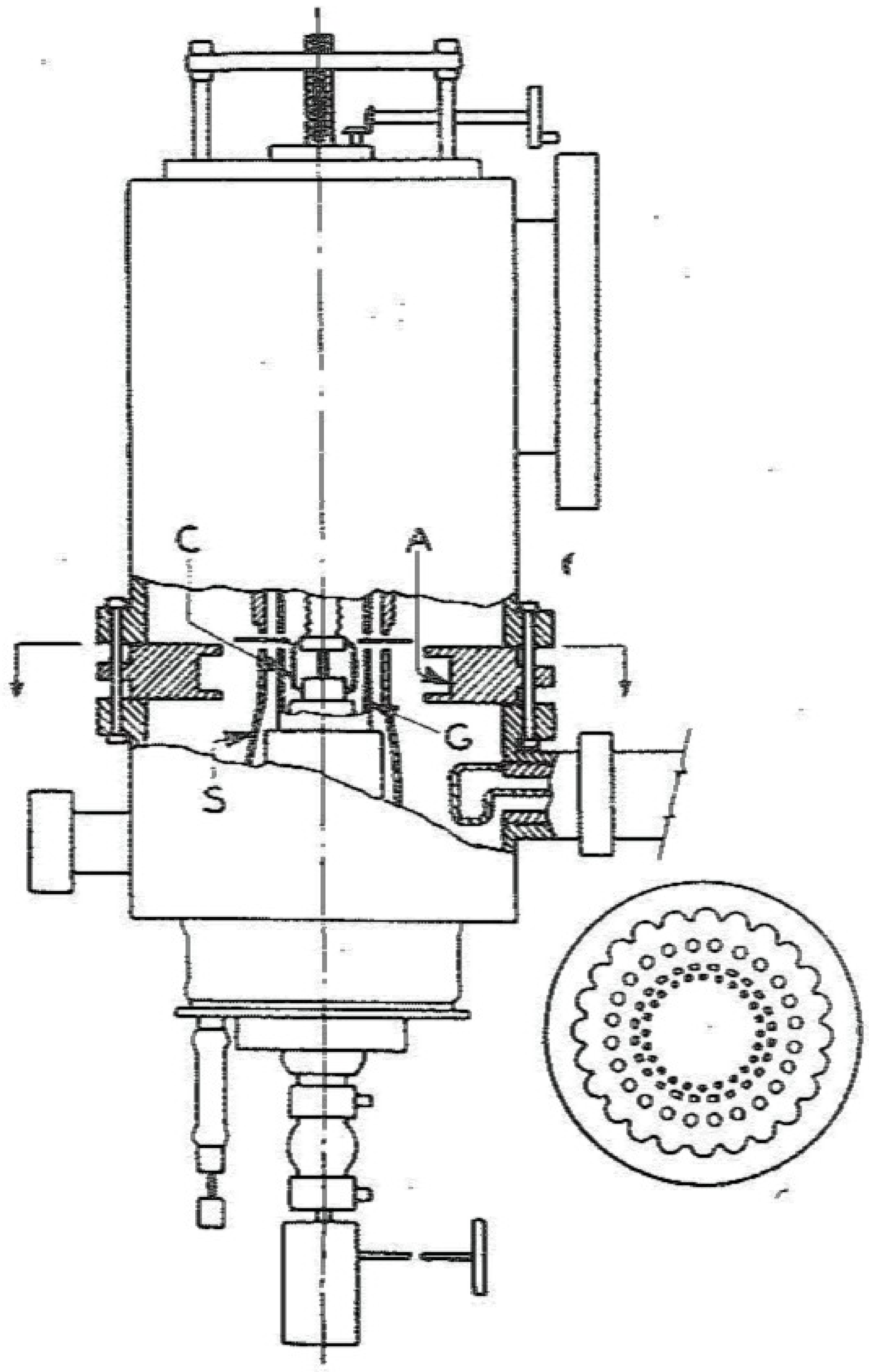

Fig. 16 *d.* – The Resnatron: cut away view and cross section: A is the anode, C Cathode, G grid, S the accelerator or screen.

war to jam the operation of German radar systems searching for Allied planes. The principles on which the tube is based were

(19) F. W. Boggs, *The Resnatron – A generator of microwaves,* « Westinghouse Engineer », Vol. 7, pp. 57–60, March 1947; W. W. Salisbury, *Most powerful uhf oscillator in existence, used to jam German radar with 50 kW at up to 650 Mc,* « Electronics », Vol. 19, pp. 92–98 February, 1946.

originally explored by Dr. Sloan and Dr. L. C. Marshall at the University of California, 1938. The Resnatron (Fig. 16), as it was

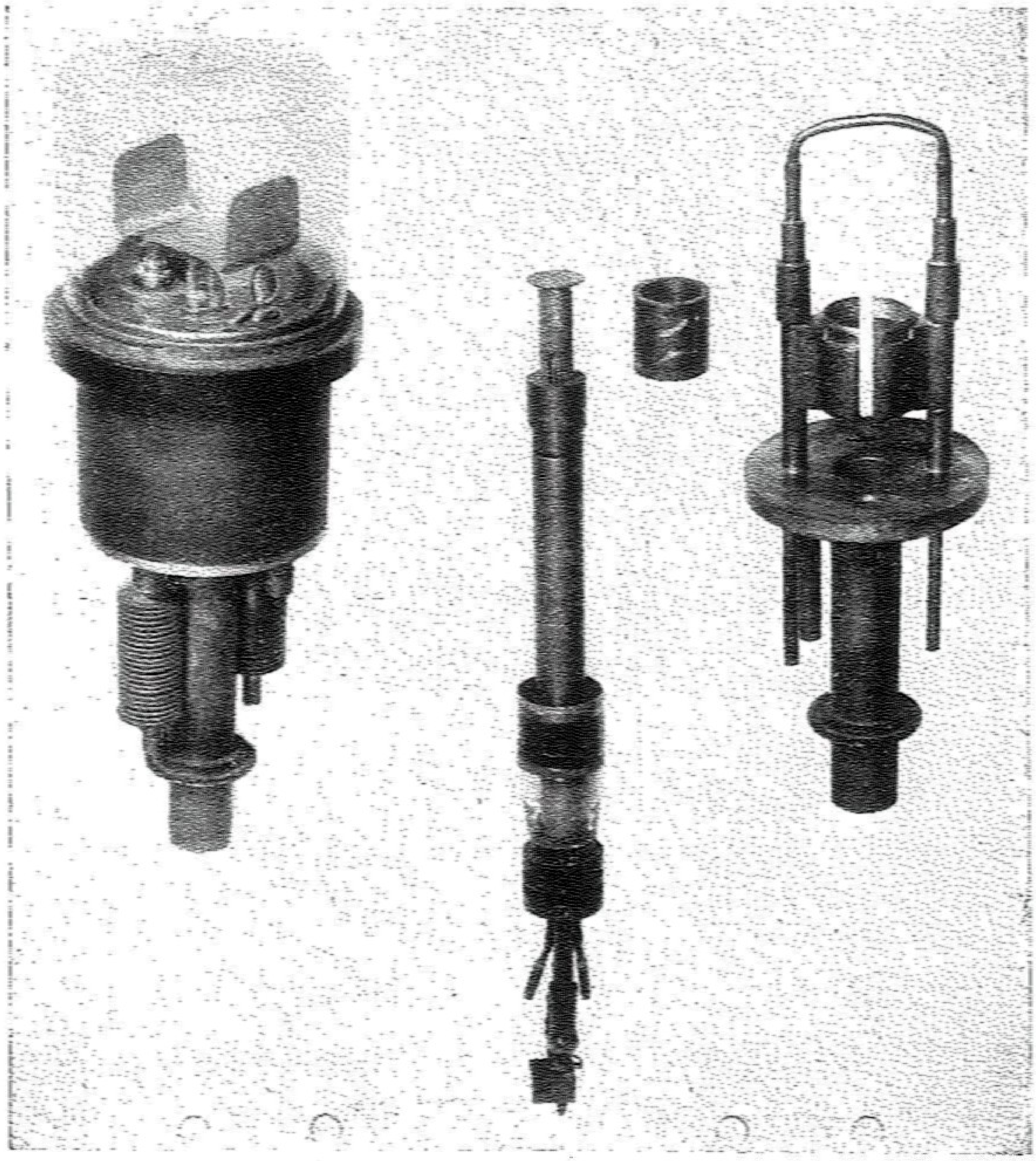

Fig. 17. – Tunable split-plate magnetron for 450 to 600 Mcs. From left to right: anode structure with a coupling loop for feeding h-f power into a wave guide; anode segment with incised grooves for water-cooling; secondary emission water-cooled cathode with a « starting » tungsten loop filament. Tube assembly with cathode removed. In the latter picture one sees two bellows by means of which a tuning ring can be slipped over the anode segments or moved away from them, thus changing tube capacitance or inductance.

actually constructed, is capable of delivering into the load 50 kilowatt of CW power, with the top value of 85 kilowatts. Its normal input is 6 amperes at 13,000 volts. The "electron" part of the tube electrodes is very short; these constitute the middle portion of two concentric cylindrical cavity resonators of annular cross section. The inner resonator comprises the cathode and the control-grid, the outer one the screen grid and the anode, all in vacuum. The cathode consists of 24 parallel tungsten strips made of 50 mil tungsten wires ground flat; it requires for its heating 1800 amperes at 2 volts. Each filament strand is very accurately located between a pair of adjacent control-grid rods, slightly behind them. The alignment of this structure is extremely important; it permits the flow of a fairly large electron current even with the highly negative grid. The spacing between other pairs of electrodes is such that the total transit time comprises from 5 to 13 half-cycles. Focusing of electron flow through the grids and suppression of secondary emission from the anode together with filament life are the major problems in designing the tube. The anode as well as the mechanical bases of other electrodes are water cooled. The Resnatron with further improvements or rather simplifications may sometime be used in television, F. M. and dielectric heating.

Another high output CW tube, which served the same purposes during the war and in peace time applications, may compete with the Resnatron, is the water-cooled *split-plane magnetron* (Fig. 17). This tube was built for several frequency ranges. An an example, one type had a mechanical tuning range from 50.8 to a 71 centimeter wave. The tuning is accomplished by a movable ring affecting tube capacitance and inductance. A secondary emission cathode at the tube axis has a magnesium sprayed surface. For starting, a filament of pure tungsten is mounted in the side of the cathode. The anode segments are water-cooled. The tube may deliver from 10 to 15 kilowatts of CW power; its efficiency is about 60 %. The tube can be frequency modulated by slightly varying the plate voltage (12 kV normal).

Traveling wave tube.

Anticipating an era of pratical applications of microwaves, one should be interested in a quite recent development in this realm, the traveling wave tube. Originated by R. Kompfner of

Clarendon Laboratory, Oxford, England; [20] it has been subject to a thorough study of a group of workers in the Bell Telephone Laboratories, New York. [21] In addition to considerable amplifi-

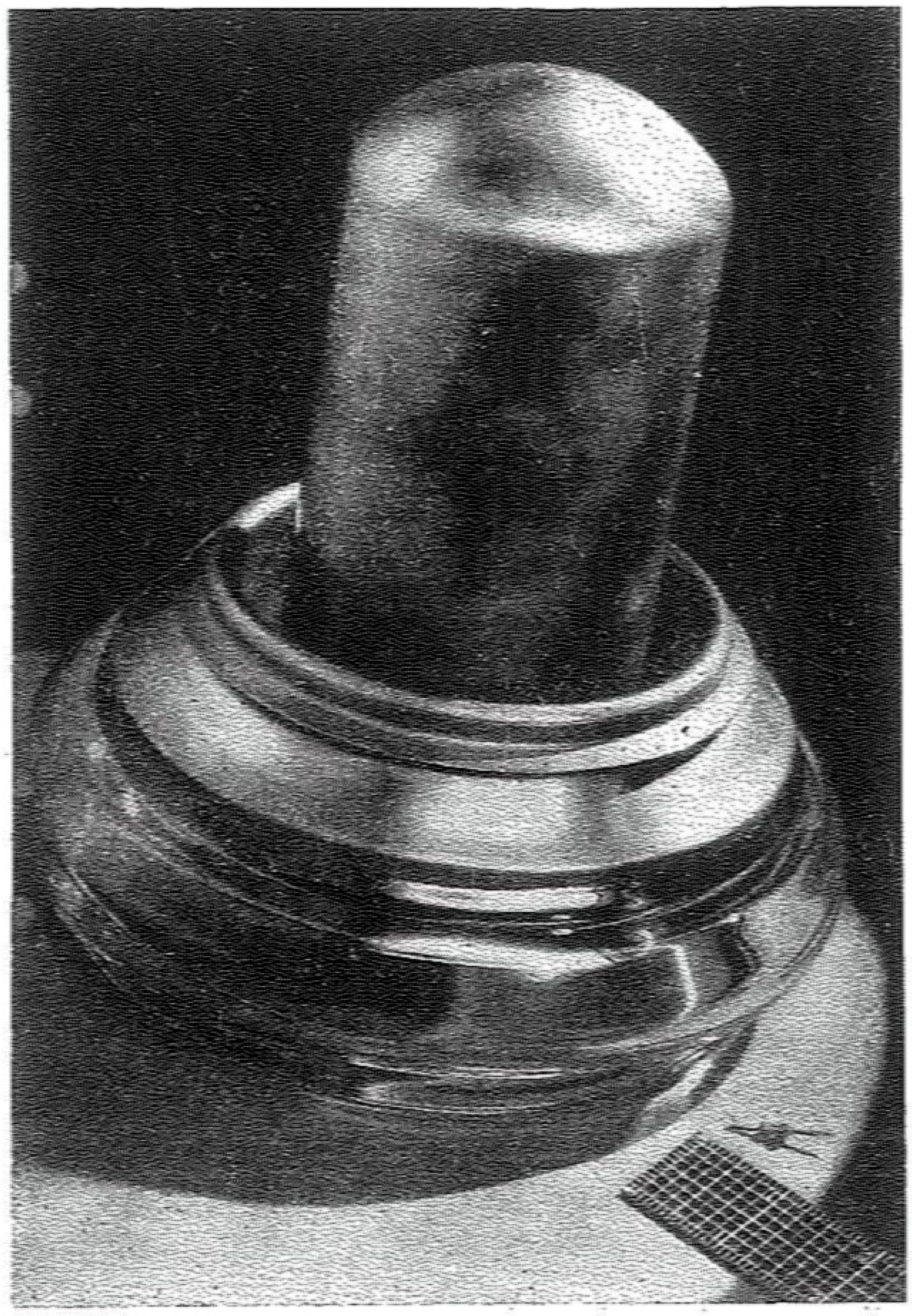

Fig. 18. – Copper anode with Kovar skirt sealed to glass.

cation of weak signals, up to 30 db, the traveling wave tube can handle an extremely wide frequency band, up to 800 Mcs. One

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(20). R. KOMPFNER, *The traveling wave valve*, « Wireless Engineer », Vol. 52, pp. 369–372, November, 1946.

(21) J. R. PIERCE and L. M. FIELD, *Traveling wave tubes*, « Proc. I. R. E. », Vol. 35, pp. 108–111, February, 1947.

may expect that the traveling wave tube can also be designed as a microwave generator.

In conclusion, it may be remarked that the designs of modern tubes for all frequencies up to the microwave region, were greatly influenced and helped by the lavish use of "Kovar" for metal-to-glass seals. Kovar is a nickel-iron alloy specially developed about 15 years ago by Howard Scott of the Westinghouse East Pittsburgh Research Laboratories for seals in the mercury vapor tubes, (22) such as ignitrons, thyratrons, etc.

Kovar does not require the precise machining of Housekeepers' seals and therefore Kovar seals are much more rigid and less hazardous than copper seals. It is interesting to note that for a long time the use of Kovar in high frequency tubes was completely excluded by all designers, on the assumption that Kovar's high resistivity and magnetic properties would incur prohibitive loss of power. However, in designing a 40 cm klystron and, later on, the 10 cm multicavity magnetron, Kovar was tried out for the sake of the greater rigidity of output sleeves connecting wave guides to the tube. Copper sleeves can be easily distorted and frequently develop leaks. The experiment showed that no disastrous loss of power is caused by the use of Kovar. And, since, practically all newly designed tubes utilize Kovar seals by brazing Kovar skirts to copper anodes (Fig. 18); Kovar is particularly adapted for making completely symmetrical ring seals for control and screen grids in water cooled tetrodes.

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(22) H. Scott, *Glass–Metal Seal*, U. S. Patent 2,062,335, July 5, 1929 – December 1, 1936; also U. S. Patent 2,062,836, December 1936.