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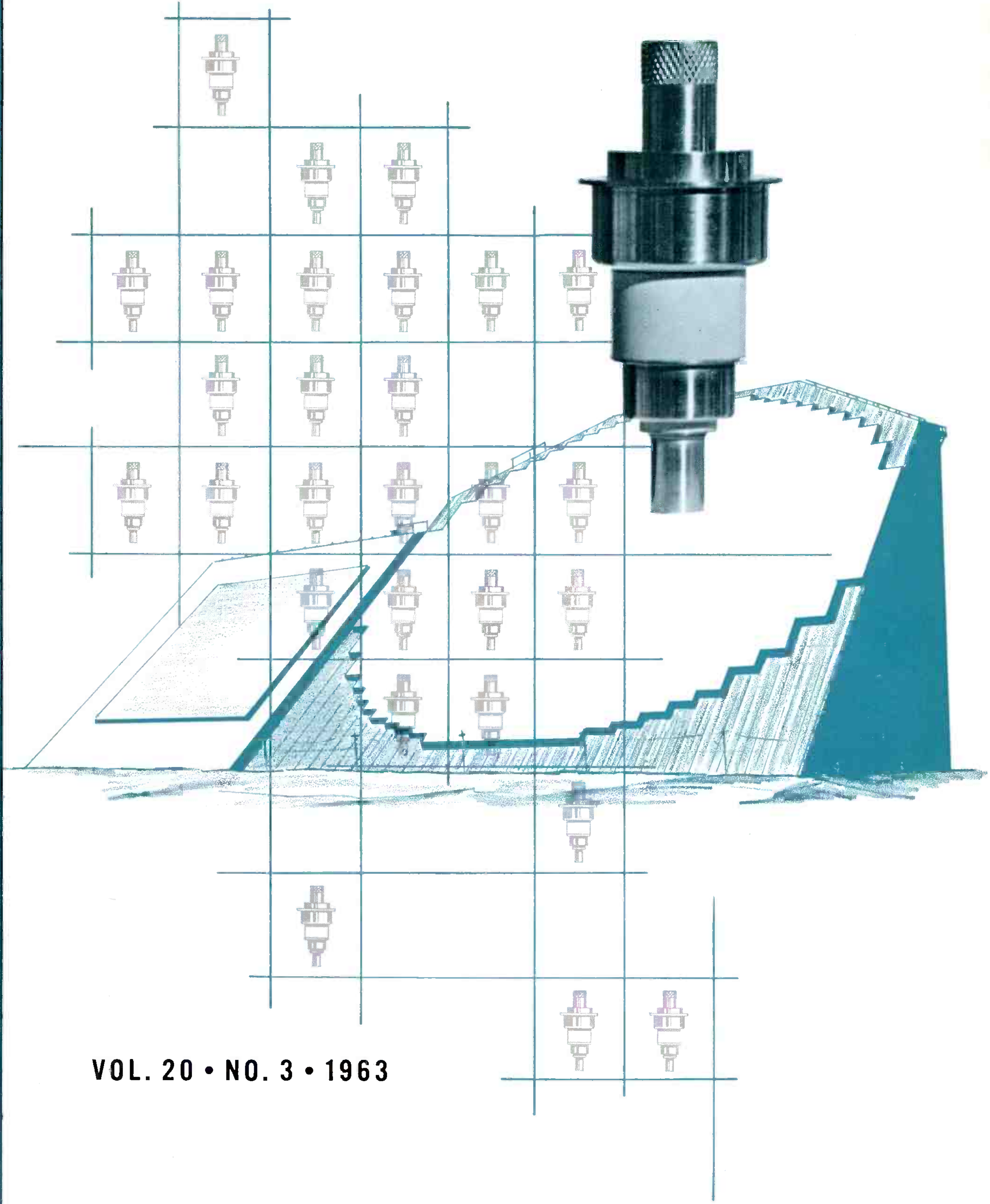

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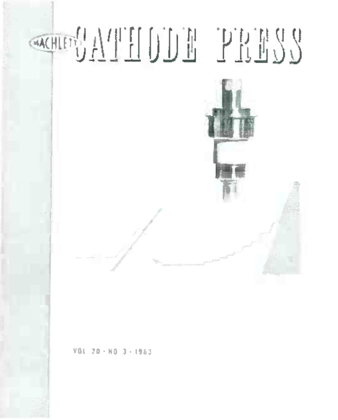

COVER . . . illustrates the U. S. A. F. Phased-Array Space Track Radar at Eglin Air Force Base in northwest Florida. This installation, and the role of the Machlett planar triode in this system, is described in the article starting on Page 2.

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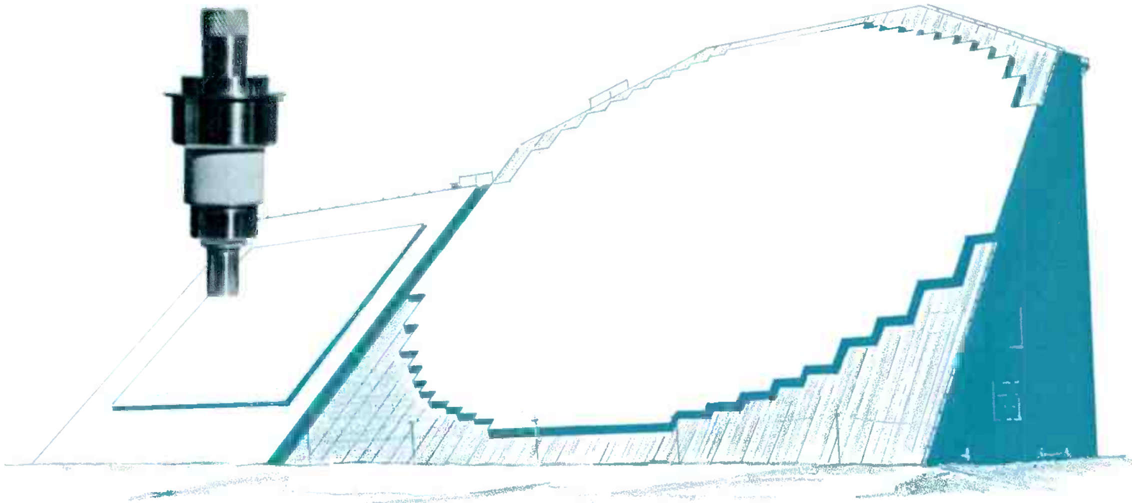


By ALLEN I. SINSKY, Principal Engineer, Bendix Radio Div., The Bendix Corporation

M. BRYAN COVINGTON, Principal Engineer, Bendix Radio Div., The Bendix Corporation

Evaluation of Negative Grid Tubes in Pulsed Applications

Present requirements for high powered radars capable of searching out and tracking many targets at thousands of miles range can best be met with the phased array radar. Large scale arrays such as those being built by Bendix Radio require high volume production of transmitter and receiver elements which must be both economical and reliable. At the lower microwave frequencies, below 1500 Mc, large quantities of negative grid vacuum tubes are being employed in the array transmitter elements because of their desirable properties, and low cost. This article will present some useful operating limits for these negative grid tubes which will allow the designer a more complete utilization of these readily available devices.

In June of 1958 Bendix Radio began work on the Electronically Steerable Array Radar (ESAR) project by first constructing and testing a 90 element linear feasibility array shown in Figure 1. This array is a complete operating radar steerable 45 degrees either side of vertical along the main axis of the building. After the successful completion of the feasibility model a large scale L-band planar-array radar housed in a five-story structure was constructed near the Towson Plant. Figures 2A, 2B and 2C illustrate L-band models and module. The face of the building is approximately 50 feet square and houses more than 8000 antenna elements located in the sloping face under a polyurethane foam protective cover. Its coverage is such that it can survey air traffic on the New York-Washington Airway and also track missile firings from the NASA Station at Wallops Island, Virginia.

At present Bendix Radio is engaged in the construction of a larger phased array radar for the U. S. Air Force. The radar, located at Eglin Air Force Base in Florida, and designated AN/FPS-85, stands as high as a 15 story building and, including both its transmitter and receiver face, occupies slightly more area than a football field. The radar shown in Figure 3 will be ready for operation by May 1964 and will be capable of simultaneously searching out, tracking, and cataloging hundreds of targets at ranges of several thousand miles.

At the beginning of the ESAR program very little information was available on the expected life of a variety of coaxial and planar triodes and tetrodes in the pulsed application for which they were to be used. There were at that time a variety of pulse derating curves published by the tube manufacturers which the customer was advised to abide by. These derating curves limited the peak cathode current for various pulse widths and duty cycles. Manufacturers were reluctant to modify these derating charts in the absence of

ALLEN I. SINSKY

With Bendix since 1957, Mr. Sinsky has most recently been responsible for the design of the transmitter module for the SPADAT radar. He has participated extensively in the design, development and evaluation of transmitter components for the AN/FPS-46 (XW-1) Electronically Steerable Array Radar (ESAR). Having been associated with this program since its inception, his work has included design and development of the following: broadband microwave circuitry including re-entry tetrode and triode cavities utilizing double-tuned circuit techniques; power coaxial components; hard tube modulation equipment for life testing transmitter tubes; evaluation of transmitter tubes to determine factors correlating life, performance, and ratings; and design and development of UHF and L-band sweep generators.

Mr. Sinsky was graduated from Johns Hopkins Univ. in 1955 with a B.E.S. (EE), and subsequently did graduate work in Microwave Transmission Theory.

M. BRYAN COVINGTON

Mr. Covington has most recently participated in the design of the transmitter circuit for the SPADAT radar. He has been associated with the AN/FPS-46 Electronically Steerable Array Radar (ESAR) program since its inception in 1958, and has worked extensively on transmitter design for phased-array applications. He has directed the ESAR design group which developed a 30 KW transmitter module at L-band. His work has included design of tetrode transmitters for ESAR using optimum gain bandwidth techniques in re-entrant cavities, and design of re-entrant high level balanced mixers. An important part of his present task is the continuing investigation and evaluation of other transmitter devices such as amplitrons, TWT's, and cross-field amplifiers.

Mr. Covington was graduated from the University of Texas in 1951 with a B.S.E.E., and University of Maryland in 1956 with an M.S.E.E.

For High Volume Consumption in Phased Array Radar

available data and, conversely, the customer was reluctant to use a tube in an application which exceeded the published ratings of the manufacturer. It was easier for the customer to select a larger, more costly tube and play it safe.

In a steered array such as ESAR or SPADAT, utilizing thousands of individual transmitter units, each requiring a tube kit of several tubes, it is not economically wise to play it safe and use the next larger size tube than one that might just do the job. This is especially true when the smaller tube might, in fact, have better life characteristics and require less heater power than a larger one. In any event, Bendix began a series of tube life tests in order to arrive at some criteria for pulse derating of cathodes.

It was generally agreed that the following parameters would effect tube life as evidenced by emission decline:

1. filament voltage (cathode temperature)
2. pulsed cathode current, pulsewidth, and duty cycle
3. plate dissipation
4. electrode voltages

A program of life testing was initiated on a group of 6442 planar triodes since this tube was intended for use in the L-band ESAR model. It became apparent at once that tube life was a function of the manufacturer as well as its application. Extensive pulsed emission testing utilizing pulsewidths from 18 microseconds to 250 microseconds and duties up to 1% at cathode current densities from 3 to 20 amps per square centimeter indicated that tube life was not materially shortened at the higher pulsewidths. It appeared from this preliminary testing that the amplitude and duration of the cathode current pulse was of secondary importance and that one of the other parameters of manufacture or operation must contribute more noticeably to tube life. Since in the above tests neither plate dissipation or electrode voltages were exceeded it was theorized that filament voltage and consequently cathode temperature plays a major part in tube life.

Because of their consistency, tube to tube, the Machlett 6442's were life tested with only heater voltage applied. Each sample was run at a different heater voltage. Emission was tested periodically by pulsing the tubes. Figure 4 reveals a marked and consistent increase in tube life as the heater voltage is lowered.

Further testing of oxide cathodes at various pulsewidths (out to 500 microseconds) and duty cycles indicated that tube life could be materially shortened if the RMS cathode current exceeded 200 to 300 milliamps per square centimeter of cathode area. It should be pointed out that tube life as

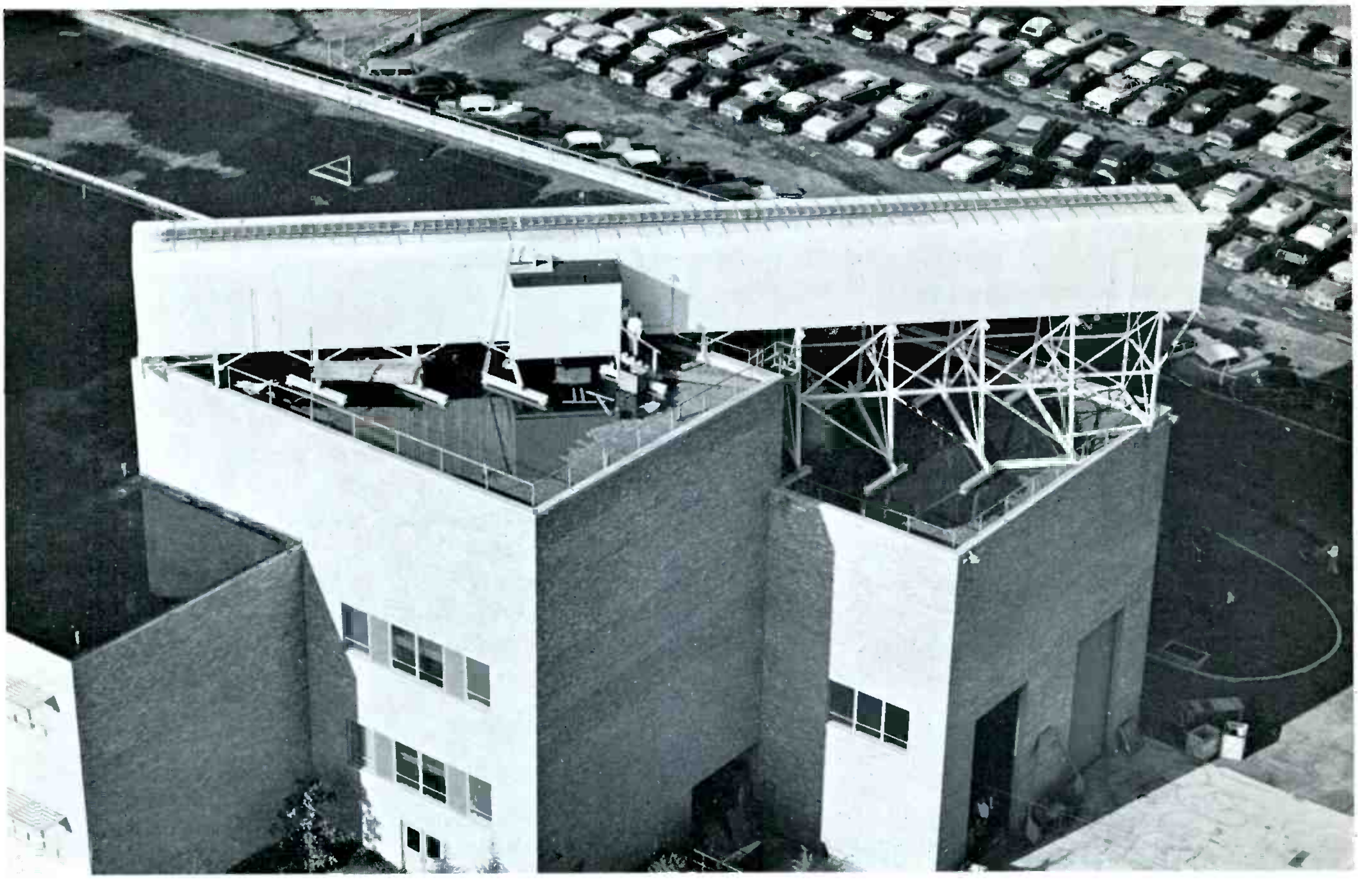
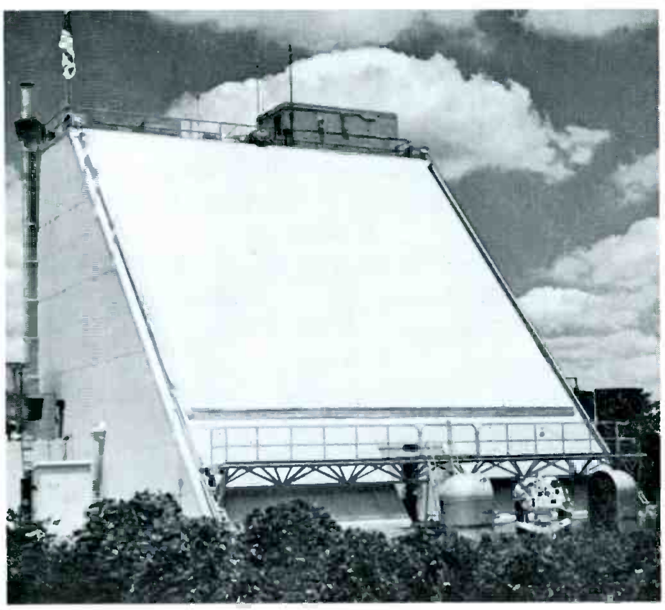
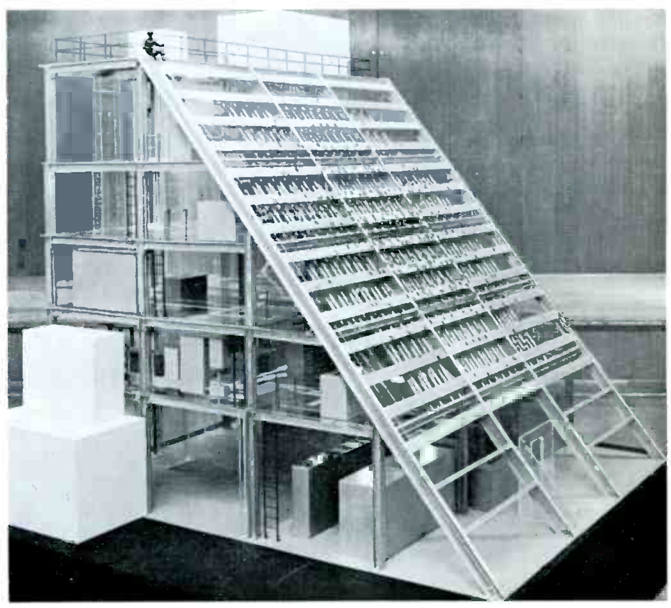


Figure 1 — UHF Linear Array, a complete operating radar, including transmitter, receiver, modulator beam steering circuits and associated controls.

Figure 2A — L-band ESAR model, a 5-story structure with more than 8000 antenna elements on the sloping face. The building face is approximately 50′ x 50′; antenna elements are imbedded in polyurethane foam for protection against the weather.

Figure 2B — Scale model of L-band ESAR radar shows equipment location. Air-conditioning of unit provides the constant temperature-humidity necessary to maintain phase control.





referred to above is defined arbitrarily as the time it takes for the cathode emission to decrease to 70.7% of its original value with constant electrode voltages applied. Figure 5 plots tube life as defined above against RMS cathode current for typical oxide cathodes. At normal operating temperatures oxide cathodes will emit peak instantaneous currents of 10 to 20 amperes per square centimeter for short pulses before emission limiting. Currents in excess of this will cause sparking on the cathode surface due to the absence of the virtual cathode normally present in the space charge limited situation. The fact that a tube normally operates under virtual cathode conditions does not mean that the cathode is not required to deliver the peak currents required in the plate circuit. Under pulsed conditions and in the frequency range in which negative gridded tubes operate, the current waveform at the cathode is essentially the same as the current waveform at the plate.

In order to verify the above criteria, several types of ceramic triodes and tetrodes, including the ML-7815 planar triode, were operated at pulsewidths of 10, 18 and 100 microseconds as well as in a standby condition with only filament voltage applied. In all cases the cathode current density was initially set at 3 amps per square centimeter. Duties ranged from nearly zero in the case of the standby tubes to .005 corresponding to an RMS current density of 210 ma per square centimeter. Filament voltages were the same among the tube types and regulated to $\pm 1\%$. In all cases the emission decline with time was not a pronounced function of pulsewidth or duty cycle.

One further restriction that must be placed on the oxide cathode is that of maximum pulsewidth. It is found that as pulsewidths are increased beyond several hundred microseconds, a current density of 10 amps per square centimeter cannot be supported by the oxide cathode and a slump or current droop results. A series of pulse tests were conducted on a group of ML-7815R's to determine the current derating necessary to prevent pulse droop at various pulsewidths. This data appears as the upper bound in the pulsed cathode derating chart in Figure 6.

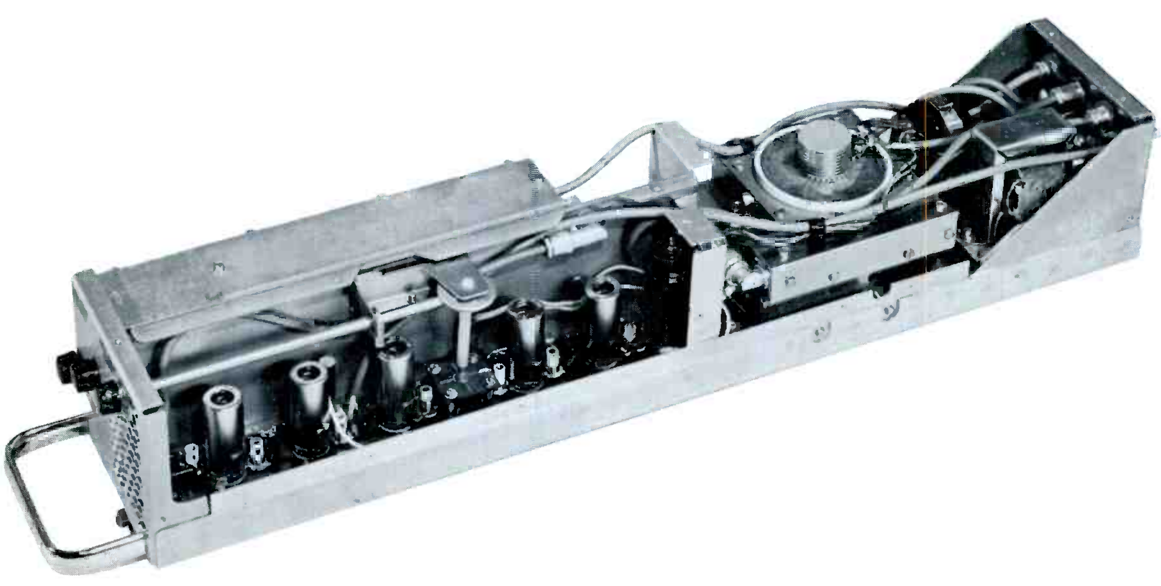
This derating chart combines these three essential upper limits of cathode operation:

1. RMS current density of 250 ma per square centimeter
2. Peak instantaneous emission of 10 amps per square centimeter
3. Current density less than that which allows emission droop at various pulsewidths

Operation at or below the levels indicated on this chart should result in tube life comparable to that attainable when the tube operates at very low current densities.

No mention has yet been made of life as a function of plate dissipation or electrode voltages. One test recently completed on the ML-7815R utilized this ceramic triode in a balanced modulator circuit operating at a dc plate voltage of 3500 volts. A 250 microsecond pulsed rf drive initiated a cathode pulse current of 1 ampere (2 amps per square centimeter) with peak instantaneous current density of 10 amps per square centimeter. The field intensity between control grid and plate in this application is about 160 volts per mil. Except for an occasional arc which was interrupted in a few microseconds by a special high voltage fuse, no noticeable shortening of life or internal damage was observed after more than 3500 hours of operation. In most

Figure 2C — Photograph of L-band ESAR module used in phased-array radar. This unit employs a pair of ML-6442 planar triodes.



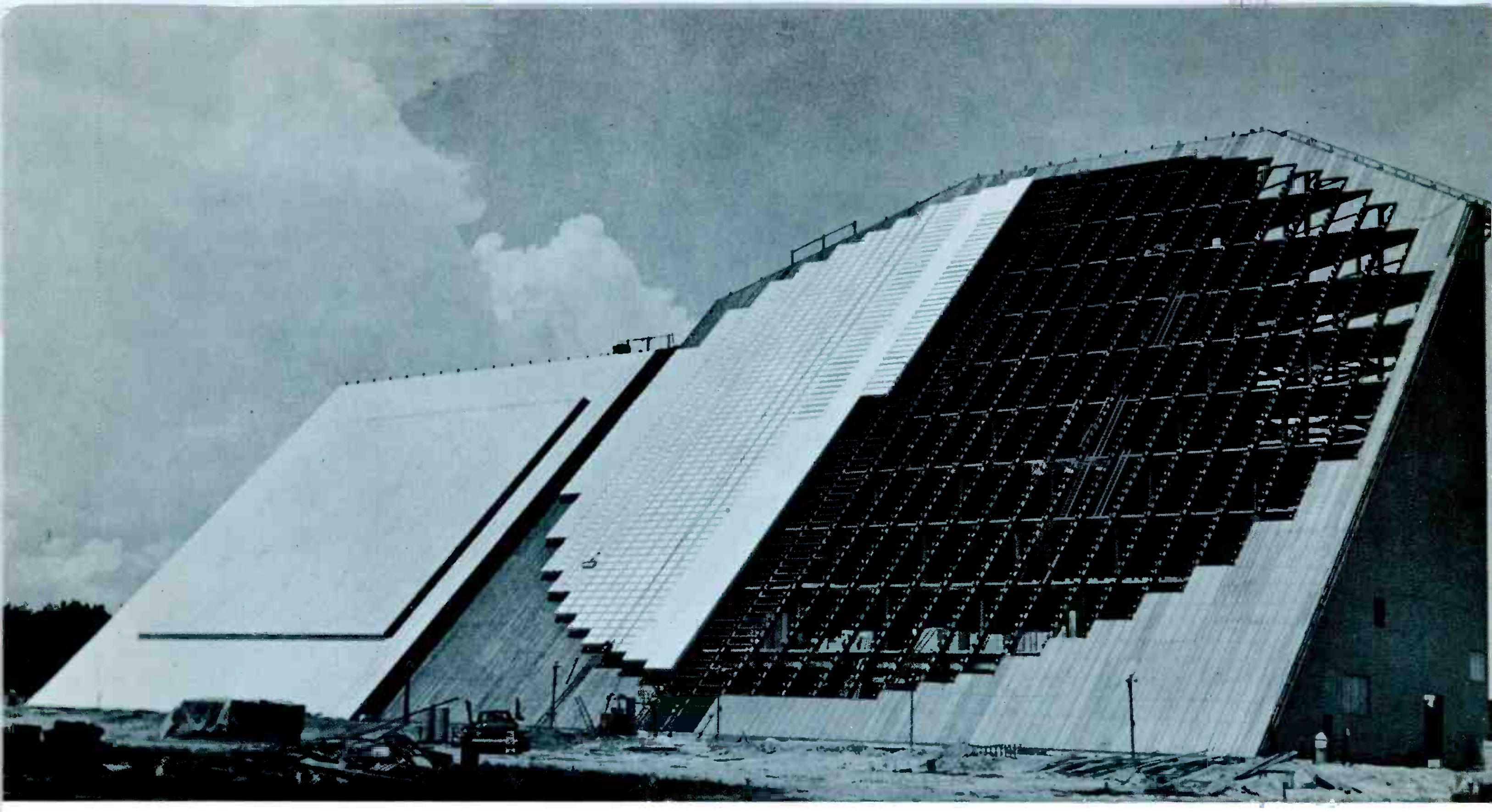


Figure 3 — View of nearly completed AN/FPS-85 Space Track radar at Eglin Air Force Base in northwestern Florida, constructed and installed by Bendix Radio under contract to the U. S. Air Force. This structure stands 150′ high, is 320′ long and 133′ deep at the base. Over 1,600 tons of structural steel were used in the construction of what would be the equivalent of an 11-story building. An 800-ton air-conditioning system maintains the required temperature-humidity conditions within the structure.

Figure 4 — ML-6442 Tube Life vs. Filament Volts.

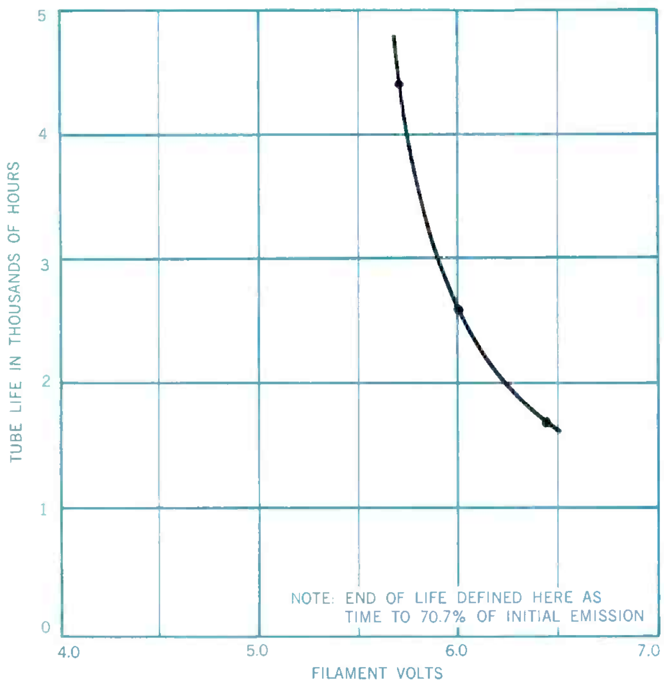
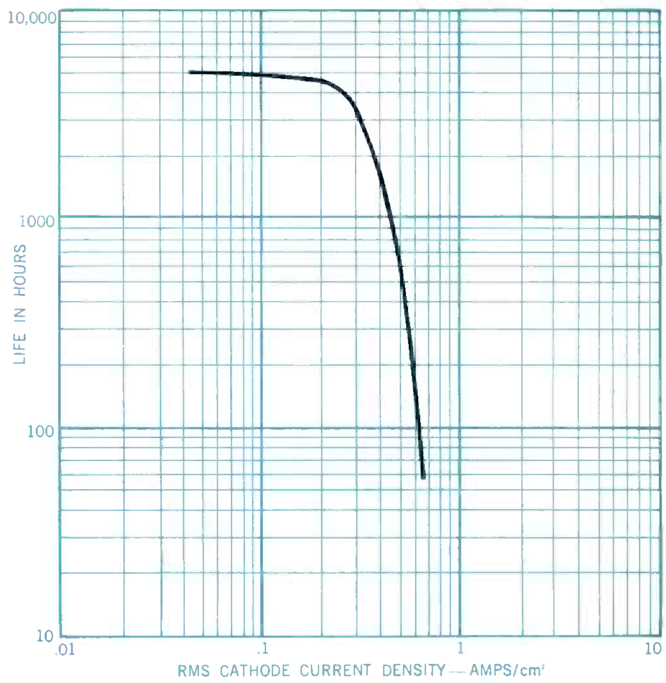


Figure 5 — Cathode Life vs. Current Density for Typical Cathode.



cases the thermal time constants of the tube electrodes are such that CW plate dissipations can be attained without excessive impulse heating of the electrodes. Voltage derating will depend on the quality of tube processing. Such factors as tube outgassing during evacuation, getter activation, and elimination of possible contaminants will effect high voltage hold-off capabilities.

Conclusions

Experience is slowly being accumulated to indicate the limits to which oxide cathode tubes can be operated. A logical use of the curves shown in Figures 4, 5, and 6 permit the use of any tube of this type to its full capability for almost any operating conditions. The only assumption in using these curves is that the manufacturer is competent in producing his product so that cathode life is not shortened by poor processing. All the data presented here was taken on production type, moderately priced tubes and not on super-processed special purpose tubes.

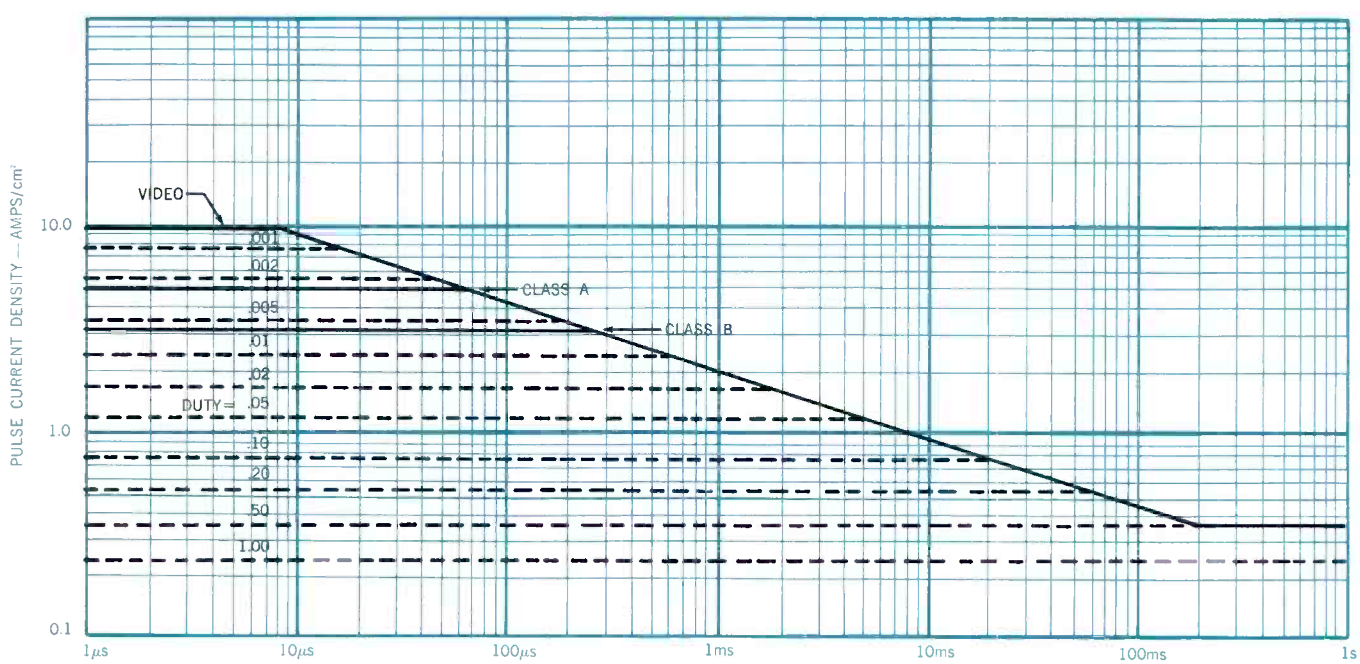
Several interesting points should be noticed in Figure 6. For one thing, no derating is necessary under any conditions to pulsewidths of 10 microseconds and for typical Class A or B operation, no pulse power derating is necessary to pulsewidths of about 100 microseconds. This is considerably at variance with present recommendations of most manufacturers. Another interesting feature is the gentle slope of the curve. A 10-times change in pulsewidth require only approximately a 2-times change in pulse current. The total charge that is delivered during a pulse increases markedly as pulsewidths are increased.

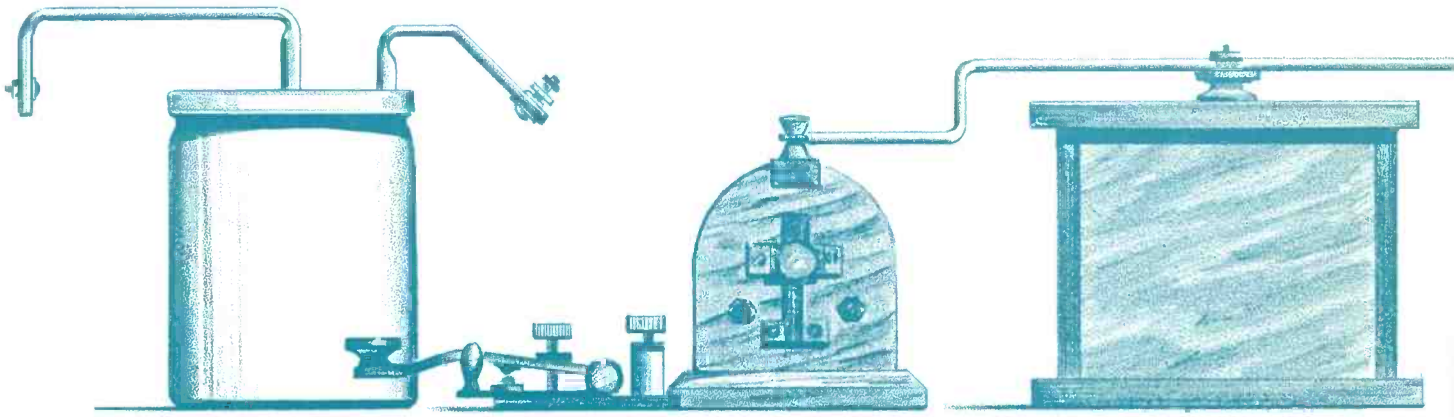
A third interesting point concerns the lower limit of current density below which droop will not occur regardless of pulsewidth. According to the rating curve this occurs at a current density of about 350 milliamps per square centimeter. This current level also determines the pulsewidth at which a tube must be operated at dc cathode ratings. The pulsewidth in question turns out to be 200 milliseconds.

In conclusion, it can be said that oxide cathode tubes are capable of operating reliably and economically in multiple tube operation if advantage is taken of the potential tube capabilities. The most needed tube improvement at this time is in voltage hold-off. Theoretically, a tube should be able to hold off many times the plate potential for which they are presently rated. Several manufacturers are presently attacking this problem with an eye toward eventually approaching the ultimate tube for multiple tube applications.

Figure 6 — Cathode Current Density Pulse Derating Chart.

SOLID LINES REPRESENT LIMITS DUE TO PEAK EMISSION & DROOP. BROKEN LINES REPRESENT LIMITS DUE TO RMS CATHODE CURRENT. BOTH LIMITS MUST BE OBSERVED. INDICATED UPPER LIMITS FOR CLASS A AND B OPERATION ARE NECESSARY TO LIMIT PEAK CURRENT DENSITY TO 10 AMPS PER SQUARE CM.





The "Primitive Years" of Electronics' History Are Unique Collection of Commander Paul G. Watson,

Although it is well known that The Machlett Laboratories has evolved from the business of manufacturing glass vacuum equipment, Crookes' tubes and cold-cathode x-ray tubes, it is perhaps not as well known that during its earliest stages Ernst and Robert Machlett[1] assisted in the developmental work of Lee deForest. It was a practice of the time that eminent engineers or medical practitioners would turn somewhat informally to small firms to have their ideas built into the structures required. Thus it was that the company of E. Machlett & Sons worked among others, with the developer of the mercury vapor lamp, Peter Cooper Hewitt. This enterprise resulted from the firm's experience with the Geissler mercury pump and, at the same time, the Geissler tube (forerunner of the Neon tube, a later project of the developing Machlett interests). The Geissler tube was a small discharge device, gas-filled, which glowed when an electrical current passed between the electrodes.

In this same context it has been noted[2] that "On numerous occasions in the early 1900's Machlett made up experimental tubes for Lee deForest, inventor (1906) of the audion, the first successful three-element electron tube for the amplification of feeble electric currents — the prototype of all radio tubes today. Published drawings of deForest's original audion show that at the start he worked with a globular form[3] of tube with extensions at either end for leads to grid, plate and filament. This, of course, was a shape of tube for which one would naturally go to an x-ray tube maker such as Machlett. Moreover, Machlett's work for Hewitt had touched incidentally on problems closely allied to those which interested deForest."

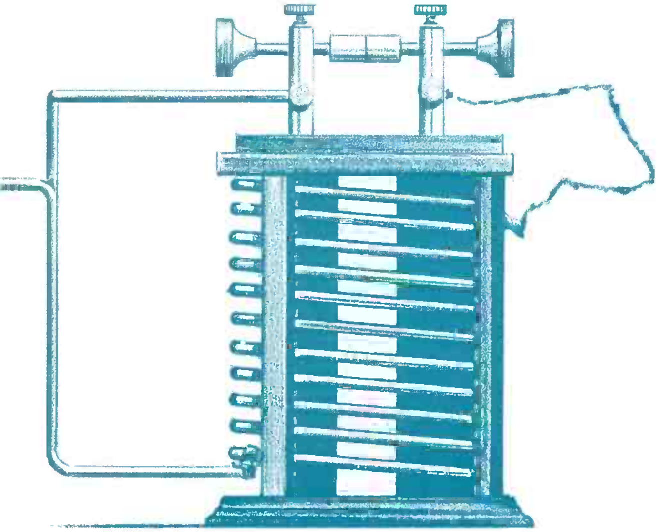
It is thus with special interest that CATHODE PRESS reviews the tube collection and early experiences of Commander Paul G. Watson, USNR (Ret.), whose electronics collection includes not only Geissler tubes and a "pulsed" transmitter of extremely early design (notably simpler than contemporary units) but also some of the earliest tubes of Lee deForest.

[1]Grandfather and father, respectively, of the late Raymond R. Machlett, founder of Machlett Laboratories, Inc.

[2]*Cathode Press*, Memorial Issue, 1955.

[3]Commander Watson comments that the original deForest triodes were "tubular" and that the spherical tubes (such as the ultra-audion oscillator) were developments of a later date. The suggestion is made, however, that x-ray tube manufacturers were turned to because others' tubes were "too soft." It appears that, in San Francisco, deForest had tubes retubulated and re-exhausted to permit proper operation — at 120 volts.

Further to this, the cylindrical envelope Audions were not manufactured beyond 1907. All single plate Audions (spherical bulb) were made between 1907 and 1909; double plate tubes from 1909 to 1915, after which came (in keeping with the times, somehow) the Model "T" Audion.



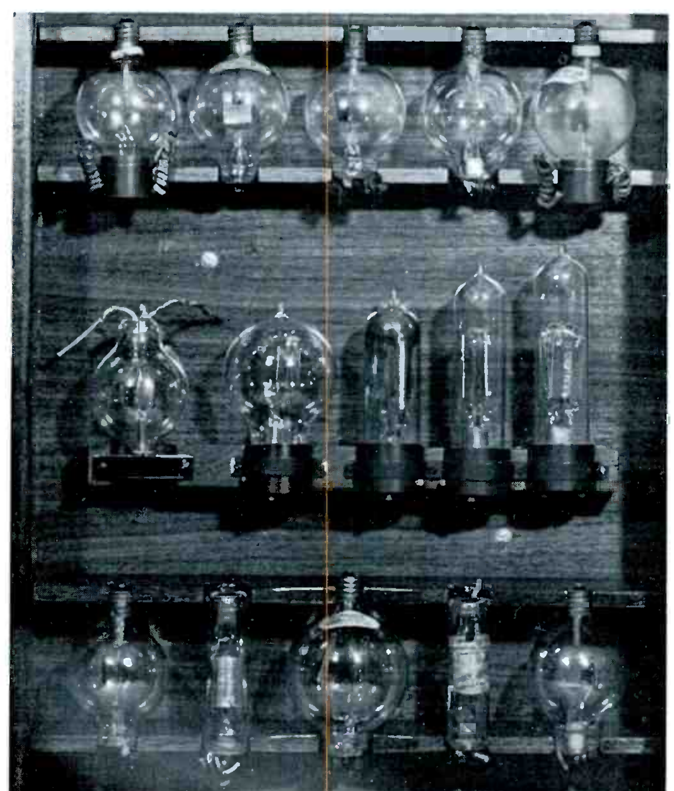
Reflected in the USNR, (Ret.)

Figure 1 — Top Row: Single plate/grid audions made prior to 1909; all are tungsten filament tubes, except 4th from the left (oldest tube in group — 1907), which employs a carbon filament. Tube 3rd from left is double plate audion made after 1909; 3½ v filament. Second Row: 1st tube (left) double plate/grid audion, 1910; next four tubes made in 1915 for Lt. Comdr. S. C. Hooper, USN, for tests as transmitting tubes. All are the first tubes in which the leads came from the base which is the early Navy "3 button" base; 4th contact is a pin on side of bayonet base. Cathode: twisted tungsten ribbon coated with "Hudson" tantalum. Third Row: 1st tube (left) employs an early device to increase emission (see Figure 1b) consisting of a fine tantalum wire wrapped around the tungsten filament. 2nd and 4th tubes are type "T" audions released on March 15, 1916, after which date no further spherical audions were made. 3rd tube is an ultra audion, one of the first tube types made as an oscillator and/or amplifier. 12 volt filament; tantalum paste on twisted tungsten ribbon. Date 1912 to 1913. All tubes in Figure 1 are deForest audions.

Commander Paul G. Watson's Electron Tube Collection

Comdr. Watson's collection is located in his home in West Chester, Pennsylvania. The collection, which includes early electronic memorabilia and equipment, consists principally of electron tubes of which there are over 1000 basic types with some 300 or more variants. Each tube is indexed by code number and has associated with it a card bearing a complete technical description. Together with the availability thus provided, the collection offers a depth in electronic time which is perhaps unique. See Figures 1, 2 and 3.

From the beginning of "wireless" telegraphy the most important single problem had been the lack of sensitivity of the detecting device. Signal transmission by means of an interrupted arc or spark gap and later by rotary gap, quenched gap and continuous arc (the Poulsen arc) was certainly sufficient for the need. But the problems of static and/or signal-to-noise ratio together with the need for component simplicity caused an early and diligent search for more effective detectors. The coherer[4] — borrowed from the scientific laboratory — was the first detector and had a



[4]The coherer was invented by Prof. Edward Branly in 1892. The device consisted of iron filings in a glass tube. When a current passed through the tube the filings would "cohere" or join together and pass current. Rapping of the tube would restore it to a non-conducting state.

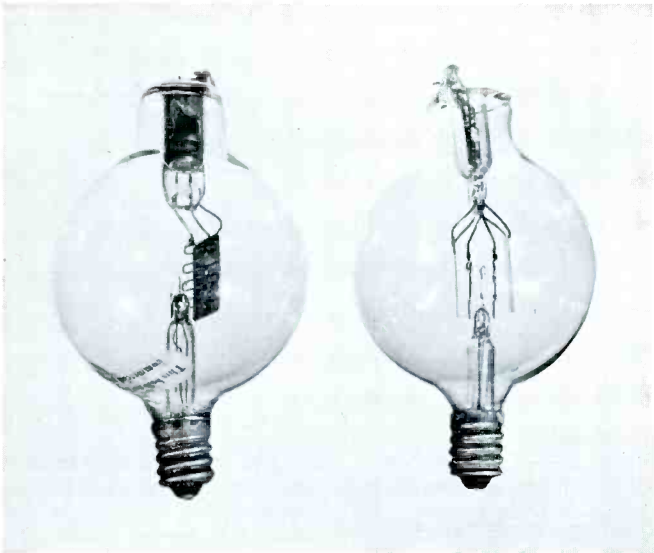


Figure 1a — Enlarged view of third and second tubes, respectively, from left, top row, shown in Figure 1.

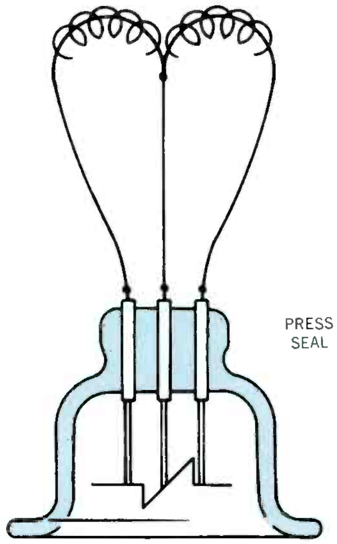


Figure 1b — Sketch illustrating early device (about 1909) to increase emission.

relatively long use. Its first wireless application was made by Oliver Lodge in 1894 and later was adopted by Marconi, forming the basis for his early efforts at signal reception. In 1903, and later in 1906, the electrolytic and crystal detectors, respectively, were invented. It was during this period that deForest "captured" the incandescent gas (which, he later learned, had nothing to do with the case) and made a gas-filled three element tube.

In 1904 deForest was active in the development of a transcontinental wireless company to compete with Western Union. During the first summer conditions had been good and the crystal and electrolytic detectors employed were satisfactory. Subsequent conditions, however, revealed deficiencies. Earlier, in 1903, he had attempted to use incandescent gas as a rectifying device. Employing two platinum electrodes, held in bunsen burner flame, with their leads connected to an antenna and earphones, deForest and his assistant, C. D. Babcock, had actually received ship signals, although the noise level was high. Other attempts to produce a "flame" rectifier failed, but lead, however, to an enclosed "flame," so to speak, an incandescent carbon filament lamp with a platinum plate. This was the first vacuum tube detector to use both filament and plate batteries.

"Dr. deForest realized at this stage of development that despite the fact that the diode worked, much of the energy received by the antenna was bypassing the tube through the headphones and battery. He wrapped the tube with tin foil which was then connected to the antenna and got better results. A second plate with the filament between the two was put inside and the results exceeded all previous experiments.

"It was this device which was named 'Audion' by Babcock, a name used to identify all deForest vacuum tubes thereafter.

"It was soon evident that the second plate, or control element (the grid), could be located more effectively between the plate and the filament, and so a small platinum plate with many perforations was prepared and another tube made with this inserted between the filament and solid plate. This was the first conventionally-arranged triode tube ever made. In subsequent models the perforated plate was replaced by a folded wire grid to lessen the cost. Needless to say this was the best design of all. Patent Number 841,387 covering this arrangement was issued January 15, 1907, and is one of the most valuable patents ever issued."[5]

He was to note some years later, in a discussion (or argument?) with E. H. Armstrong that ". . . anyone who has had considerable experience with numerous audion bulbs must admit that the behavior of different bulbs varies in many particulars, and to an astonishing degree. The wing potential-wing current curves for different bulbs, or even for the same bulb at different times, under differing conditions (filament temperature, etc.) vary widely." To which Armstrong replied "Dr. deForest speaks of the great differences existing between the wing potential-wing current curves. It will be readily understood by those familiar with the laws of the conduction of electricity through gases that such is bound to be the case where any considerable amount of gas is present in the bulb. The potential at which progressive ionization of the gas begins is dependent, among other things, on the pressure; and hence the upper parts of the

[5]P. G. Watson, Cmdr. USNR Ret., "The Electron Tube," *Radio & Television News*, November 1954, pps. 67, 166.

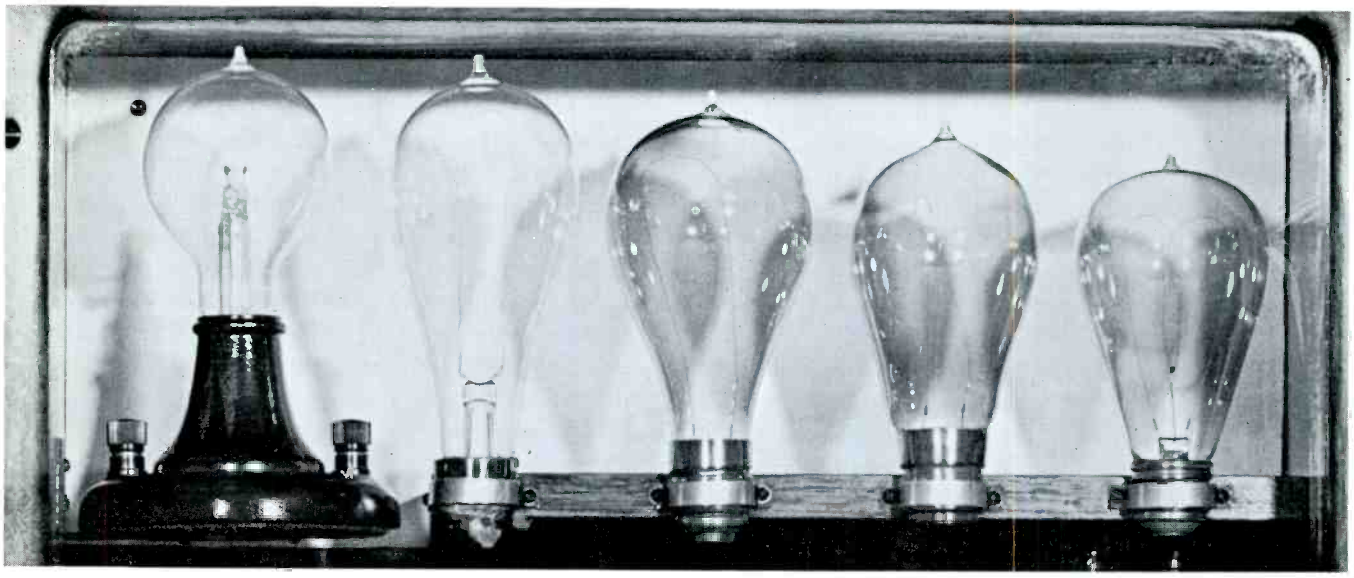


Figure 2 — Lamp "A" is a replica of original Edison bulb made at Nela Park, Cleveland. "B" is an original bamboo filament electric lamp made in Edison "set-up" at Menlo Park, N.J. between 1881 and 1886. Bamboo was coated with asphalt before carburizing to increase strength. "C" is early 1800 "U" filament carbon bulb (maker unknown). Sides of "U" are about 1¼" apart. "D" is early 1800 bulb with wide leg "U" filament, but with top, or return bend of filament turned so that there is top-to-bottom 90° twist of the "U"; this method gave circular light pattern. "E" is early form of "squirted cellulose" filament dating from 1894. It was successful replacement for bamboo filament, and was standard design until replaced by tungsten filament (MAZDA) lamps.

wing potential-wing current curves vary, but the lower parts, the only place where the electron relay can be operated, are invariably of the same general shape. With the modern methods now available for producing very high vacua, it is a simple matter to construct audions whose characteristics are for all practical purposes identical. With these high vacuum bulbs, the astonishing differences of which Dr. deForest speaks disappear to an astonishing extent."[6]

Obscured by the towering technical implications of the Audion is a commercial note to indicate that tube rebuilding is as old as time. Commander Watson comments: "The tubular 'Audions' (bottom row, Figure 1) were known as Type 'T' and were made first in 1915 when the spherical envelope was discontinued. It also presented a major change in sales policy, as prior to this time it was necessary to return an old bulb (tube) to purchase a new one. Competitors had been selling tubular vacuum tubes below the original deForest price, hence his entrance into this field selling an 'Audion' with the non-return policy."[7]

DeForest's work with the audion was to take him farther. In the cascaded amplifiers he had built (see Figure 4) "howling" conditions occurred; tubes producing these unwanted sounds were called "singers," and from these were developed the "ultra-audion" tubes, or oscillators. Here now was the means for displacing the arc, the alternator and the spark gap for signal transmission. Although deForest used the ultra-audion to simplify and improve existing heterodyne circuits he did little else with electron tubes. But he had, of course, already done a great deal.

Amateur Radio Station 3BV

Mention has been made of the electrolytic detector. This explosive device, which utilized the destruction of a gas bubble to allow passage of current, was invented by Reginald Fessenden in 1903. Both the Fessenden detector and electrolytic interrupter were used in the initial installation of amateur station 3BV. The equipment (Figure 5) was put into operation in the summer of 1912 — with the license 3BV being granted four years later in 1916. The 3BV license granted to Paul G. Watson was among the first 600 given in this country. He later used the call 4XX, Savannah, Georgia, for experimental work on what were then known as "high frequencies".

On a cold clear night 3BV West Chester, Pa. would reach quite a distance, with its ragged spark sound. 3BV, which operated from 1912 to 1917, came on the air via an antenna having 4 parallel wires, each 90 feet long and 60 feet high. Commander Watson describes his equipment in a personal and, in places, amusing, memoir:

"The receiver (Figure 6) consisted of a coil of wire of about 300 turns of #24 cotton covered magnet wire wound on a 3 inch wooden cylinder well saturated with orange shellac. A bare strip was carefully sanded down the top center of the coil and a sliding contact arranged on a square

[6] E. H. Armstrong, "Some Recent Developments in the Audio Receiver," *Proceedings of the IEEE*, August 1963, pps. 1094, 1095.

[7] P. G. Watson, Ibid., p. 166.

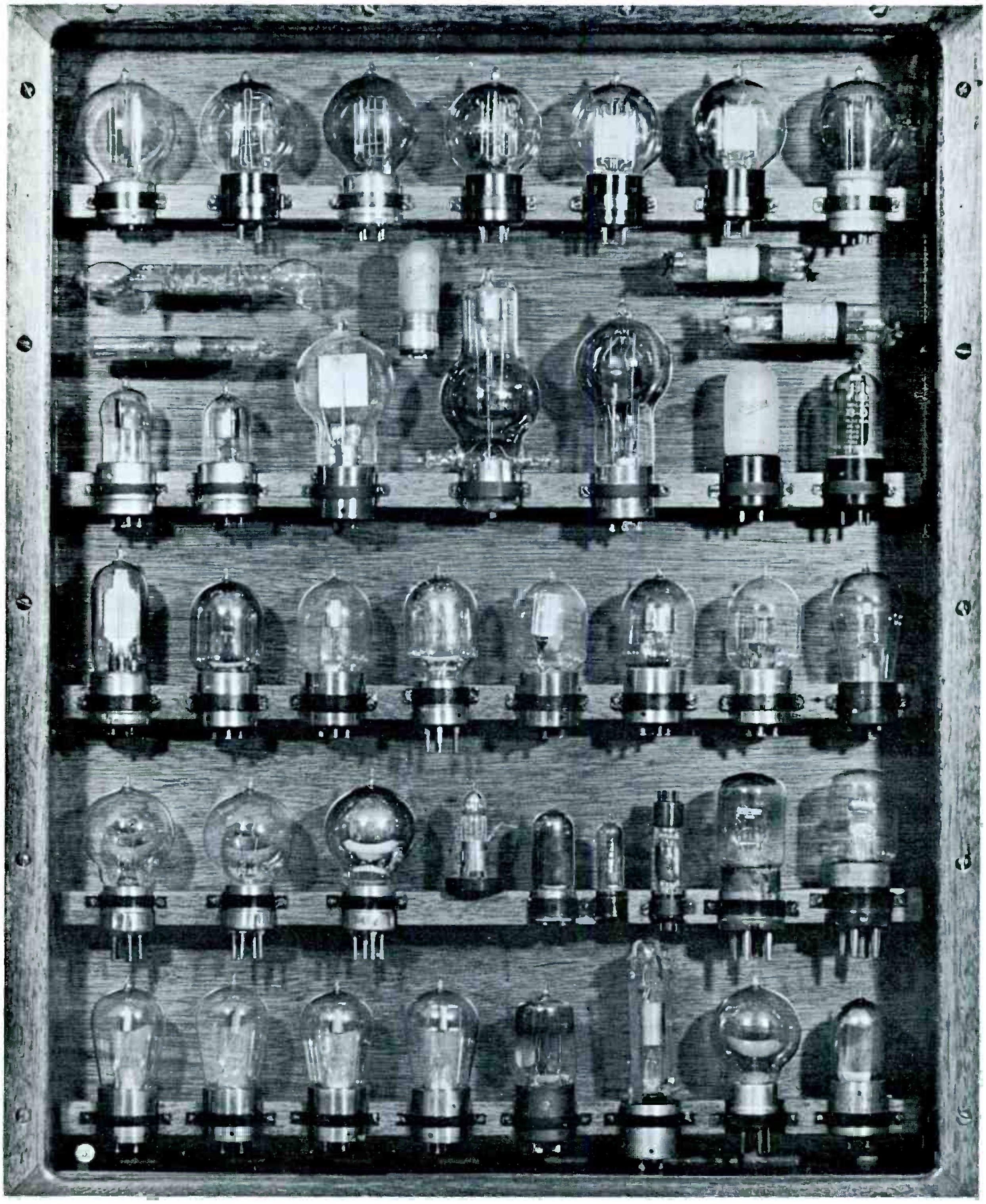
bar to contact the individual turns of the inductance, for the purpose of tuning. The antenna was connected to one end of the coil and the ground connected to the sliding contact.

"A tapped fixed condenser was shunted across this variable inductance to increase its tuning range (see schematic drawing of receiver, Figure 7). The tapped fixed condenser was in reality and effect, a four point switch with three individual condensers of different capacities to provide the necessary variation in tuning range. The first point on the switch was 'open', with no capacity connected, the second point had a five leaf condenser, the third point had a ten leaf and the fourth a twenty leaf condenser. The condensers were so set in capacity value that when the slider reached the maximum number of turns on the coil with the switch on the first or 'open' position, the same frequency could be reached by placing the condenser switch on the second point and moving the coil slider back to the middle of the coil. In the same fashion, when the maximum inductance was in on the second point, moving the switch to the third point and the slider to the middle of the coil brought back the same frequency, and so it was on the fourth point, until a maximum wave length of slightly over 2500 meters was reached with all of the inductance and the large condenser in use.

"In 1910 the electrolytic detector (Figure 8) was the best means known to receive audible radio signals, at least for amateur purposes. It consisted of a microscopic silver plated platinum wire, known as 'Wollaston wire,' the tip end of which was immersed in a small cup of dilute nitric acid. When the cup and the wire were connected in the radio circuit, slight gas polarization collected on the tip of the wire, giving unilateral conductivity and rectification of the impressed radio signal which became audible in the head phones. Later, possibly two or three years, this messy electrolytic detector was replaced with a 'Cat whisker' and galena (lead sulphite) dry crystal.

"Early in 1912 a 'one inch' 'Bull Dog' spark coil was purchased from the Electro Importing Company, 233 Fulton Street, New York. A spark gap was made and mounted on an old switch base, and we then had our first transmitter (see schematic drawing of transmitter, Figure 9). Operating from 8 dry cells and keyed with an old Western Union telegraph key, donated by Thomas Smith, the W. U. operator in West Chester, we were on the air with a little squeaky

Figure 3 — Top Row: Early W. E. tubes (l. to r.) WE-201-A; 205-D; VT-2; 104-D; 101-F, 102-F; 216-A. The 201-A dates from about 1915, has a 3 button "old Navy" base. The VT-2 (third tube) made for U. S. Government in WW-I was very widely used in 5 watt transmitters. Rest of first row were used as telephone amplifiers. Second Row: (four horizontal and 1 vertical tube). Top left is the Geissler tube. 3 colors when lit (forerunner of neon signs). Made in Belgium about 1912 or 1913; lights from a spark coil. Under the Geissler tube at the left is a "Weagant tube" made by the Marconi interests (American Marconi of which Roy Weagant was Chief Engineer) about 1912 to 1914; triode tube, cylindrical envelope, filament, small conical in center of tube, grid is a flat disc (round) placed crosswise in the tube just above the point of the conical filament. Plate is electro-plated on the outside of the envelope, a band about ⅝ inch wide; nominally a triode. Center tube in the 2nd row, and the 6th tube in the 3rd row are Sodion Detector Tubes, sometimes called Donle tubes. In the second row, vertical in the middle is "S-13" Sodion, for use with the old UV-199 tubes (3.3 filament volts) and in the 3rd row is the "D-21" Sodion tube for use with 201 and 201-A tube with 5 volt filaments. Gas filled detectors, glowed orange color in use through frosted envelope. Made in early 1920's by Connecticut Telephone & Electric Co. of Meriden, Conn. The two tubes on the left, mounted horizontal, are the two types of Audiotron tubes made by E. T. Cunningham on the West Coast before 1915. Very "soft" excellent detectors, two tungsten filaments; in wide amateur use before WW-I on the West Coast. These are the tubes which forced deForest to change to the Model "T" tubular Audion, March 15, 1916, and caused change in sales policy. Third Row: First two tubes are "VT-21" tubes made by deForest for the U. S. Govt. in WW-I. Used as detectors largely — not so hot — interchangeable with the standard W. E. "VT-1" tube; "Hard" vacuum in some cases; irregular performance. Third tube is a deForest Thermionic Rectifier developed after WW-I for use in low powered transmitters (Telephone). Fourth tube is a deForest transmitter "H" triode (after WW-I) designed for HF and some VHF bands for amateur use; 50 watt tungsten filament. RCA released 852 shortly afterward to compete in HF and VHF (of that day). Fifth tube is a deForest "Singer type" triode with elements very similar to the "H" tube. Used on a base to fit into low power deForest radiophone sets. Some were sold for low power AM BC, and others were used by amateurs. Fourth Row: First tube is famous "VT-1" W. E. tube, the universal U. S. Govt. receiving tube of WW-I; 5 volt oxide fil., had 10k gold tips on the four prongs to avoid contact troubles, improved version of original WE-203-A tube. Second and third tubes are Mooreheads — the type made during the patent freeze, by agreement between American Marconi, deForest and Moorehead — made in San Francisco; discontinued when RCA was formed and took over the Fleming Valve patents from Marconi. Fourth tube is a Moorehead, but mounted on a British base. Made for the British during WW-I. Fifth and sixth tubes are Electron Relay tubes for amateur use. The elements are identical with those in the audiotrons shown in the Second Row; however, these tubes are mounted on regular 4 pin "shaw" bases made by Moorehead, and E. T. Cunningham in San Francisco before WW-I. Fifth Row: First three tubes are "Fotos" design made by Metal of France, before WW-I. Very similar to the British Army "R" tube which is shown in the 6th row as #7. All have the European standard base of that period — triodes; 5 volt tungsten fil., moderate degree of vacuum. The 8th and 9th tubes (last two on right) are Telefunken made for the German Army in WW-I. Element details are an exact copy (or vice versa) of the French tubes in this row. Sixth (Bottom) Row: First four tubes are General Electric (VT-14, CG-890, CG-1162, TB-1, made for the Government before and during WW-I; predecessors of the RCA line of early receiving tubes. TB-1 was a two element tube used to control voltage on the wind driven aircraft generators in WW-I. Rest are triodes, tungsten filament, various voltages. Fifth tube is a "Model A" audio amplifier tube made by Magnavox for use in their 1920-24 audio amplifiers. Sixth tube is a tubular Audiotron such as shown in the second row, but mounted in a 1920 adopter so it could be inserted in a conventional 4-prong "shaw" (short pin) socket.



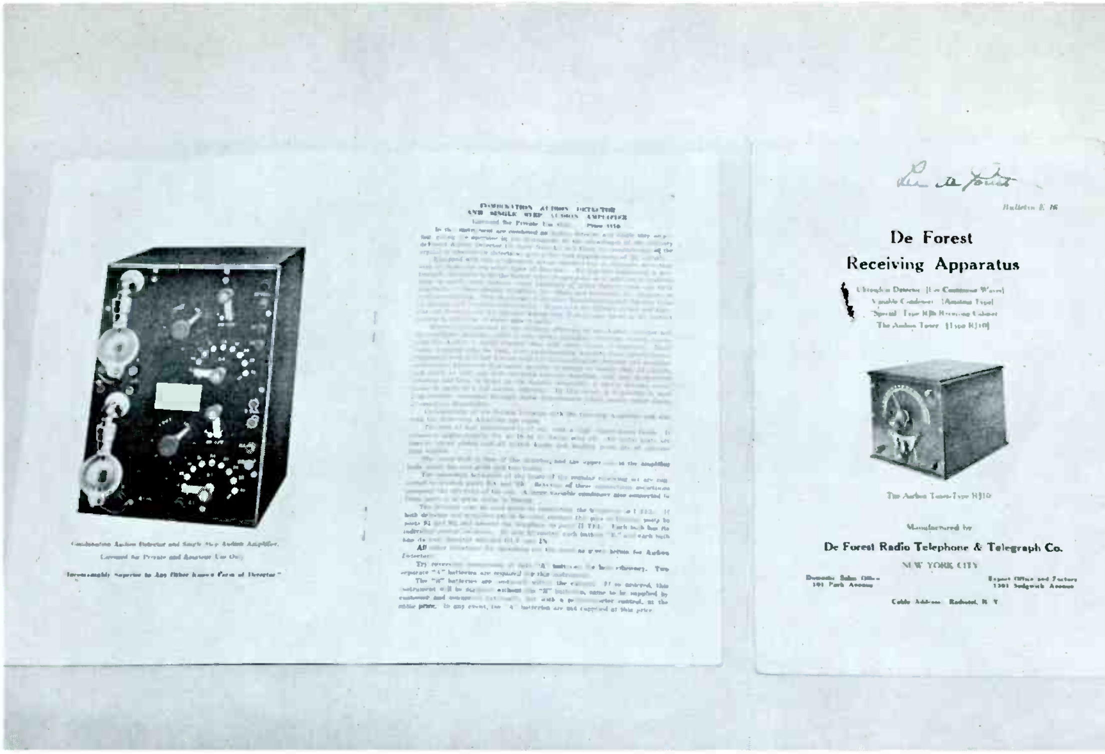


Figure 4 — A reproduction of part of the brochure covering the deForest Audion detector and amplifier, Type RJ 10, for the "higher class of operators." The description which accompanies the RJ 10, which was sold during the period 1909 to 1915, reads:

"COMBINATION AUDION DETECTOR

AND SINGLE STEP AUDION AMPLIFIER

"Licensed for Private Use Only. Price $110

"In this instrument are combined an audion detector and single step amplifier, giving the operator in one instrument all the advantages of the ordinary deForest Audion Detector (in itself from 1.5 to 3 times the sensitiveness of the crystal or electrolytic detectors) plus a five-fold amplification of the signals.

"Equipped with this combination set an operator has an immense advantage over all those who use other types of detectors. We find this instrument is particularly attractive to all the higher class of operators, as in addition to enabling them to easily read stations many hundreds of miles further than can their neighbors, it tremendously simplifies the labor, and heightens the pleasure of wireless receiving. This on account of its utter dependability, and freedom from all delicate and frequent adjustments. When once the battery switch and rheostat are correctly set the operator knows that if he is once tuned to the distant station he will hear it every time it calls.

"Moreover, on account of the extreme efficiency of the Audion detector and the negligible damping which it adds to the secondary receiving circuit, tuning with the Audion is much sharper than with other forms of detectors. Much looser coupling may be used, with corresponding freedom from interferences. Especially does this last feature hold for the combination detector and amplifier instrument, wherewith it is easily possible to couple so loosely that all signals, and static as well, are first rendered entirely inaudible with any unamplified detector, and then to bring up the signals (especially if slowly damped wavetrains be used) to a full audible intensity. By this means it is possible to read long-distance messages through static disturbances which render other forms of receivers inoperative.

"Combinations of the Audion Detector with the two-step Amplifier and also with the three-step Amplifier are made.

"The case of this instrument is of oak, with a high waxed piano finish. It measures approximately 9½ by 18 by 15 inches over all. All metal parts are heavily nickel plated and all switch knobs and binding posts are of genuine hard rubber.

"The lower bulb is that of the detector, and the upper one is the amplifier bulb, which has two grids and two plates.

"The secondary terminals of the tuner of the regular receiving set are connected to binding posts RA and RE. Reversal of these connections sometimes increases the efficiency of the set. A large variable condenser also connected to these posts is of great value in tuning.

"The detector may be used alone by connecting the telephone to I TEL. If both detector and amplifier are to be used, connect this pair of binding posts to posts S1 and S2, and connect the telephone to posts II TEL. Each bulb has its individual control switches. B1 and B2 control each battery 'B,' and each bulb has its own rheostat lettered OUT and IN.

"All other directions for operating are the same as given herein for Audion Detectors.

"Try reversing connections of both 'A' batteries for best efficiency. Two separate 'A' batteries are required for this instrument.

"The 'B' batteries are contained within the cabinet. If so ordered, this instrument will be supplied without the 'B' batteries, same to be supplied by customer and connected externally, but with a potentiometer control, at the same price. In any event, the 'A' batteries are not supplied at this price."

The caption under the detector-amplifier reads: "Combination Audion Detector and Single Step Audion Amplifier. Licensed for Private and Amateur Use Only. 'Incomparably Superior to Any Other Known Form of Detector'."

This signed catalog is contained in the Watson collection.

signal, completely untuned.

"By mid-summer of 1912, a magazine article came to hand showing a deForest station with glass plate condensers and a 'helix' to tune with. This was supposed to 'peak up' your radiated energy and double the transmitting range.

"A condenser was made by cleaning off several glass photograph negatives, shellacking tin foil on each side, staying back an inch from the edge, and when the whole stack of 8 plates was completed they were tied into a bundle and immersed in mineral oil. The whole assembly was then placed in a dust tight box.

"The 'helix' previously mentioned was the tuning inductance, 10 turns of #6 bare copper wire spaced ¾ inch between turns on an 8 inch diameter wood column support. It was used as a common inductance, or auto-transformer, in both the antenna and the spark circuit, tuning being accomplished by moving either the spark circuit clip, the antenna clip, or both if needed after the proper number of condenser plates had been determined.

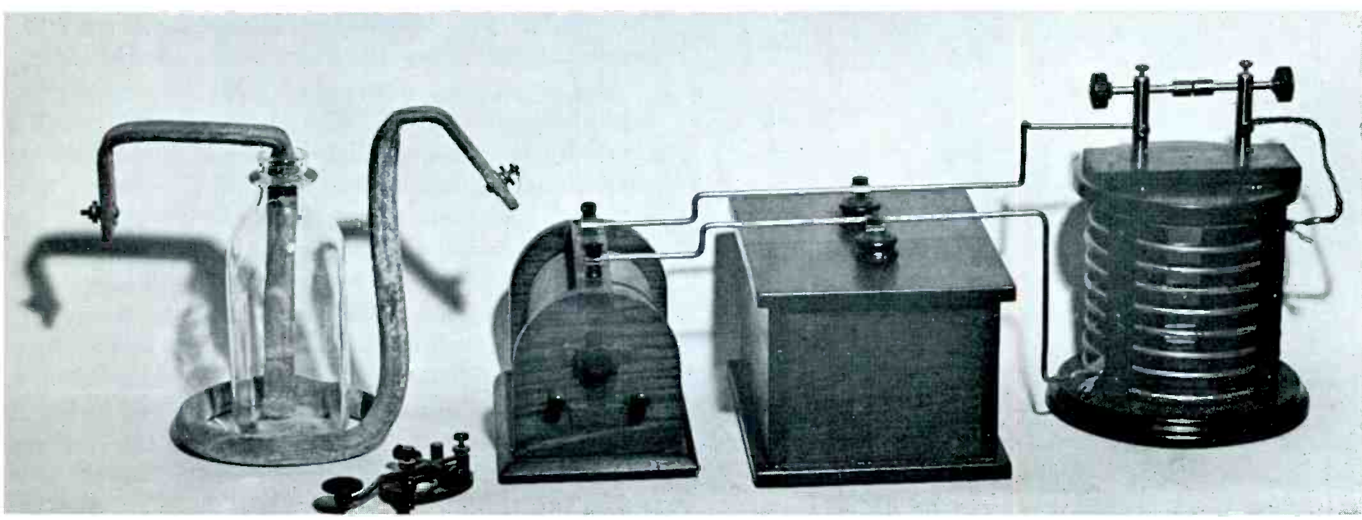
"In 1912 alternating current was available in very few places and certainly not in West Chester. We wanted 'power' and we had power available in the form of 115 volt direct current for house lighting. We had a 'tuned' transmitter now, so during the late summer of 1912 an electrolytic interrupter was made to work the transmitter directly for the 115 volt D. C. line. The only change necessary to the apparatus was the bridging out of the mechanical vibrator on the spark coil, and to connect the key and the coil primary through the electrolytic interrupter to the power line.

"Because of the unusual interest of many people in the details of the electrolytic interrupter, a picture of its original elements and a cross-section drawing of its assembly accompany this article (see Figures 3 and 8). It consists of a stoneware crock of about two gallon capacity, filled to a depth of 4 inches with a sulphuric acid solution. A quart milk bottle was drilled with a file end at point 'A' (on the cross-section drawing) until a hole about 1/16th inch in diameter was made in the corner formed by the bottom and side of the bottle. The bottle is then set in the acid in the crock. Since there is a hole in the bottle it fills itself to the acid level in the crock. A lead pipe electrode is placed as a contact in the acid inside the bottle and another lead electrode is placed in the acid outside the bottle, but in the crock. By this arrangement, and the electrical conductivity of the acid, the only electrical connection between the two electrodes was the small column of acid in hole 'A' in the milk bottle. When the 10 ampere current passed through this column of acid it promptly vaporized, therewith opening the electrical circuit. The acid then fell back together by gravity pull, closing the circuit, whereupon it promptly vaporized and again opened the circuit. This cycle of interruption would continue so long as the telegraph key was closed and current flowed.

"It is well to note that the primary winding of a coil intended to operate on a six to ten volt source of power was connected through the electrolytic interrupter directly to the 115 Volt D. C. lines for many years, without damage resulting to the coil. It was fortunate in the beginning that a shortage of available acid made a relatively weak acid solution necessary in the interrupter, for it was found that not only the frequency of the interruption cycle could be changed, but also the current flowing to the coil could be regulated by strengthening or weakening the acid solution. Also in the use of the interrupter, the hole in the glass bottle was gradually enlarged, and possibly two or three times a year new bottles had to be placed in service. The hole would enlarge to as much as an eighth of an inch in diameter and currents would become excessive.

"Since the operation of the interrupter depended on the decomposition of the sulphuric acid solution, a very vile

Figure 5 — The direct coupled spark transmitter of station 3BV. This transmitter, which was operated from 1912 to 1917, consisted of these units, reading from the left: electrolytic interrupter (see Figure 10); telegraph key; auto transformer; glass-plate capacitor; high voltage transformer and spark gap. Approximately 1.5 kw pulse power was generated. See schematic drawing, Figure 9, and text for description of operation.



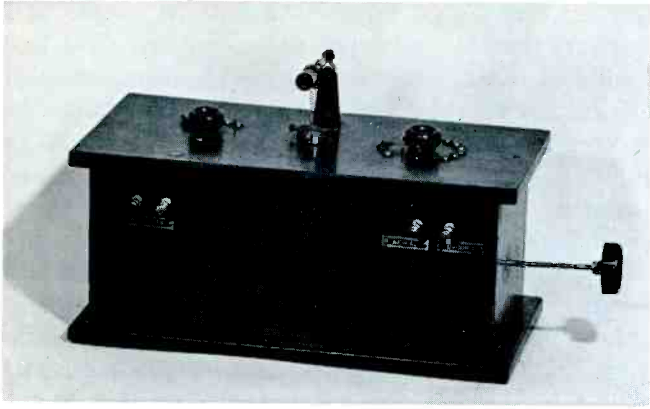


Figure 6 — Station 3BV's receiver. The first model (1910) employed an electrolytic detector. This model, a revised version, employs a crystal detector.

odor would soon be noticed when the transmitter was in operation. Hydrogen gas was one of the products of this action and on one occasion there was an explosion in the box covering this device of sufficient force to break it apart and spill the crock. As the bottle hole enlarged, heat became excessive and on one occasion soon after starting operations, the bottom of the crock dropped off and a gallon or so of acid went through the floor down onto the kitchen range. It occurred at 1:00 A.M. on a winter night, when there was a fire in the range. Very promptly 'all hands' were awake, the range turned a beautiful orange color, and the house was opened for a general airing. The radio operator's backside was most uncomfortable from a low frequency oscillation generated by his father's hand. The interrupter was messy, it stunk, but it was a satisfactory solution to getting radio power on the air under the prevailing conditions.

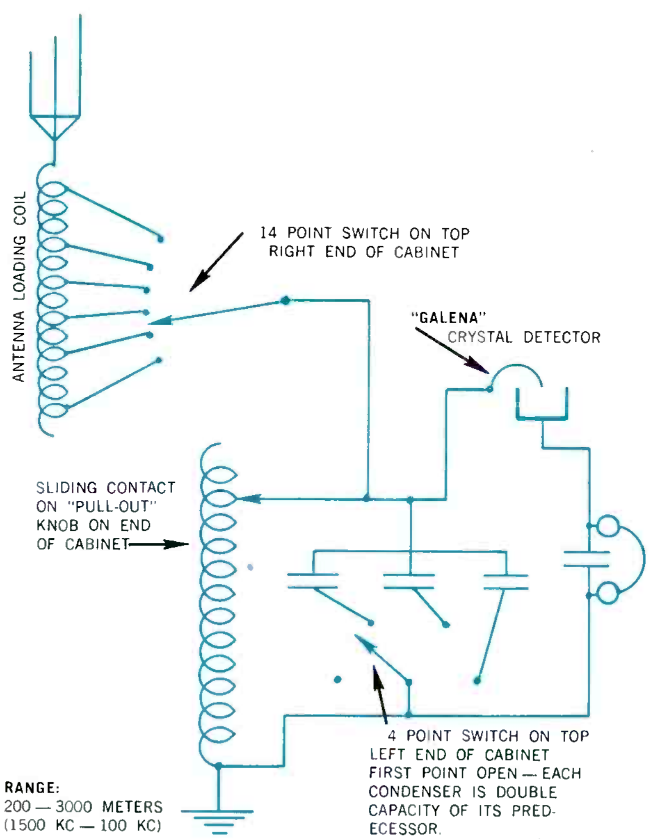


Figure 7 — Schematic drawing of the 3BV receiver.

"Since the interrupter of this transmitter was in modern phraseology, a modulator producing the signal tone which would go on the air, it should be realized that the cutoff was made by a small explosion, and the return by gravity and the note or tone produced resembled nothing but what is now made by a leak in a bad pole transformer. It was ragged, irregular, had a resemblance to static crashes, and was easily lost in such interference during the summer months. Such spark notes were very common at the time, including some of the commercial and military stations. When higher frequency interrupters using mercury and mechanically driven elements were used to produce a note of about 120 cycles, it was considered of sufficient importance that a patent was granted on the 'high frequency' spark note. By 1916, 60 cycle generators and synchronous spark gaps were soon in use, and a very pleasing musical note replaced the early ragged spark. The introduction of the higher toned spark note was the first step of progress in overcoming the static interference which dogs all radio operation.

"A natural question at this point is, what distances did this equipment cover? The spark coil operated on batteries at the very beginning was of course local, not over a ten mile radius, and when the power was applied to the coil the distance was extended to occasional contacts up to 150 miles, with a power input to the coil of about one and one-half kilowatts of D.C. The receiver brought in many stations, particularly at night, up and down the Atlantic Coast, from Newfoundland to Key West. Many stations inland, particularly around the Great Lakes were heard regularly at night. The receiving range depended on the atmospheric conditions and the hour of the day, much as do today's receivers.

"Another question often asked, what frequency (wave length) did you use? The most accurate answer is 'don't know'. The only thing available in the early days was the publication from time to time of 'technical' articles stating that a coil and condenser of the dimensions given would give you 200 or 300 meter wave length. No such thing as a wave meter (frequency meter) existed outside of the Government agencies and a few commercial laboratories. The method used in the early days to obtain the working wave length (frequency) consisted of a flashlight bulb affixed to the antenna leads in such a manner that it could be moved up and down the output coil until maximum brilliance was obtained. Naturally much interference resulted with the commercial services and the Navy.

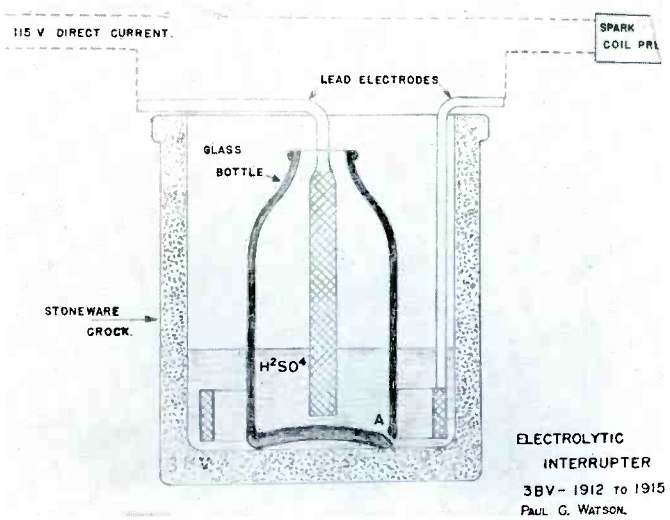


Figure 8 — Schematic drawing of an electrolytic detector of the type first used on 3BV's receiver.

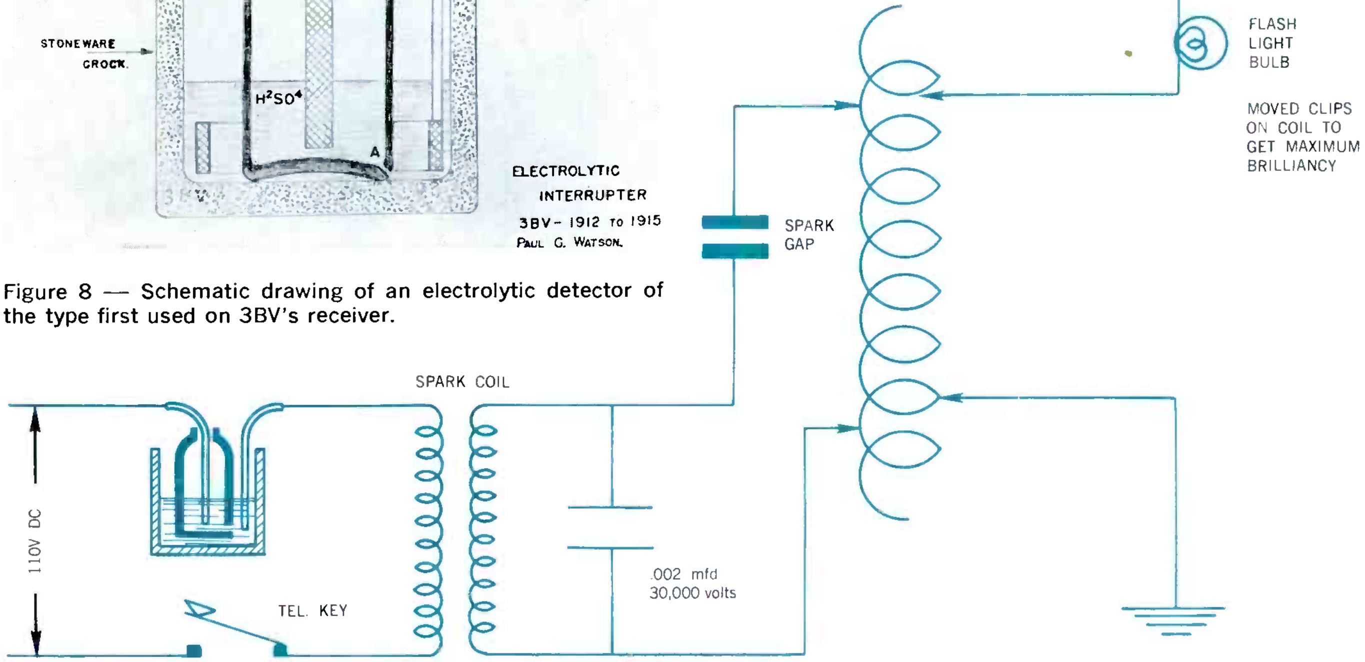


Figure 9 — Schematic drawing of the 3BV transmitter.

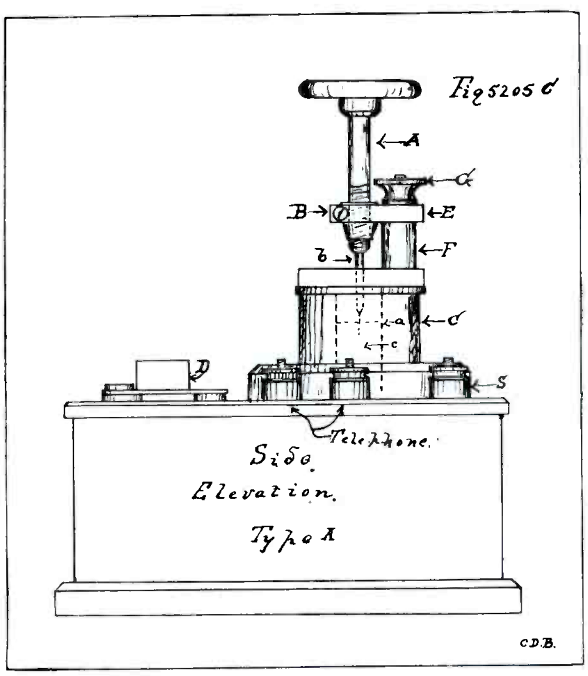
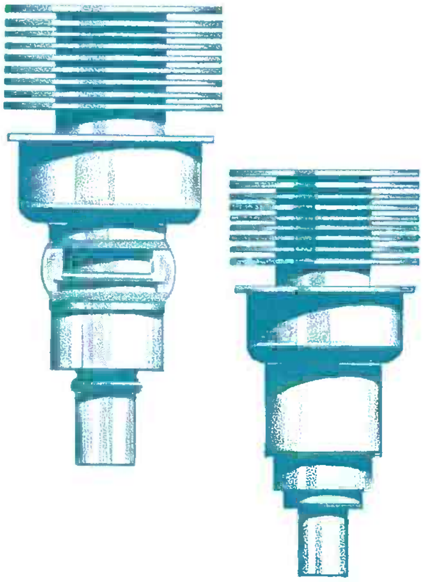


Figure 10 — Drawing of 3BV's electrolytic interrupter or "pulse modulator."

"The 3BV license was received January 20, 1916, after a visit from 'Pop' Cadmus, Dept. of Commerce Radio Inspector in charge of the 3rd Radio District. It seems we had used very bad judgment in heckling the station at the Philadelphia Navy Yard. So as a penalty we had to get a 'license.' At the time of his visit Mr. Cadmus checked the transmitter and said we were on about 475 meters. He said to keep below 300 meters and 'loosen up the coupling' and there would be no problem with the Navy Yard".

Conclusion

A foreshortened sense of time is one consequence of the technological world in which we live, as is shown by this brief glimpse into the first days of electronics — a period not even sixty years away. Between then and now are extremes which are almost incomprehensible, as well as those which are merely astonishing. In 1912 malicious interference and jamming was a commercial practice; tube voltages were high at 120 vdc; "200 meters" was high frequency; it was a good trick to get Chicago from West Chester on a clear night — just a while ago it was a good trick when we reached out 32 million miles and recorded a noisy voice near Venus.



The Television Translator:

An information relay device to extend the range of broadcast signals has been developed to meet a need which, not so long ago, was non-existent. This device, an automatic, unattended re-broadcast transmitter named the Translator, was first adopted for the purpose of bringing commercial television signals to remote areas — or to those areas simply not able to receive direct television broadcasts. Amply fulfilling its role, the Translator now numbers over 1500 in daily use. Signal conversion is vhf-to-uhf or uhf-to-uhf with vhf-to-vhf having recently been added. Translators are expected to play an increasingly important role as the UHF field develops. The emphasis on educational television is also expected to result in the use of many Translators to provide strong signals for distant schools.

Essentially, the function of the Translator is to re-broadcast an original signal on a frequency sufficiently different to assure elimination of ghosting or other interference. The Translator must be a self-contained device capable of operation in remote locations (mountain tops, for instance). It must provide automatic cut-off protection, normal on-off control from an accessible location and transmit an identifying call at suitable intervals.

One of the most active Translator manufacturers is Electronics, Missiles and Communications, Inc. Their recently marketed models, HTU-100 and U-HTU-100 incorporate Machlett planar triodes, either the ML-2C39A or the ML-7211, depending on the power output required, the latter tube providing the greater power. These models receive signals from channels 2 to 13 or 14 to 83, depending on the model, and re-transmit normally on a channel between 70 through 83. Units have been made with outputs on lower UHF channels and also on VHF channels.

General Description Models HTU-100 and U-HTU-100

Perhaps the most desirable attribute of any piece of equipment is a "turn-it-on and forget about it" degree of reliability. This must certainly be true of any remotely located gear. To provide this reliability the HTU models employ a combined tube and semiconductor complement. Individual enclosures (Figures 1 and 2) for maximum tube cooling (hence, good tube life) are provided for the tuned line tripler, mixer and final amplifier stages. Tune line circuitry aids in tuning stability.

Each Model, HTU-100 or U-HTU-100, 100 watt Translator, is self-contained and consists of two cabinets: RF and Power Supply. Each cabinet has its own requisite metering. Meters for the rf cabinet include: forward power, reflected power, % reverse power, final plate current, mixer plate current, tripler plate current (as well as similar meters for monitoring the grid). The front panel of the rf unit also includes provisions for changing the relation of aural to peak visual power (from 50% of visual to 10% of visual).

Figure 3 is a block diagram of the HTU-100 Translator. The U-HTU-100 is similar but with circuitry for a UHF input. Both models employ dual conversion, bringing the input signal to a 40mc if frequency. Amplification, band pass shaping, AGC, and automatic cut-off functions take place

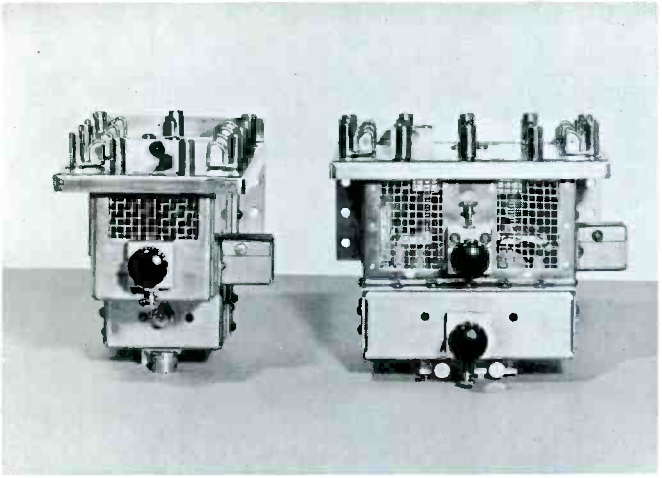


Figure 1 — Tuned line tripler stage (left), tuned line amplifier stage (right) of Translator Models HTU-100 and U-HTU-100.

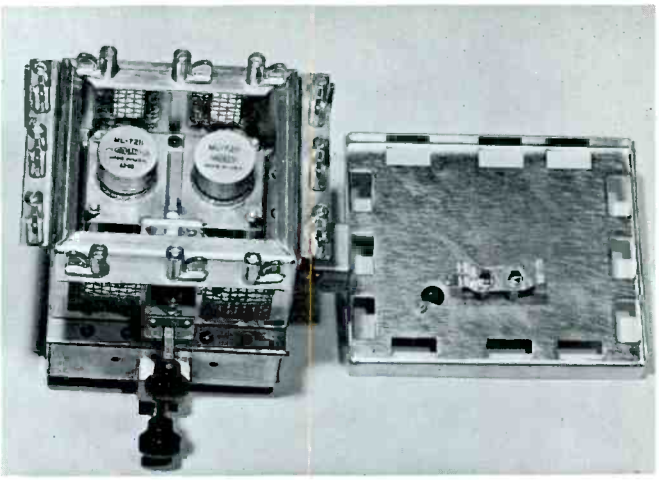


Figure 2 — Individual enclosures to permit maximum tube cooling are employed for the tuned line tripler, mixer and final amplifier stages. The final amplifier stage is illustrated.

A Broadcast Service

in the if section. The input rf amplifier employs a cascode circuit at VHF. A double triode (type 6922) provides low-noise operation in this duty. The cascode circuitry provides both stability and gain and eliminates the need to neutralize the triode sections. From the rf amplifier the signal is mixed and passed to the first if amplifier (which contains the sound level control circuit), thence to the second and third if amplifiers, the last of which contains the AGC and control detector. The signal at this point has been developed for re-broadcast but remains in the 40mc if range. A tripler section (ML-2C39A) feeds into the second mixer (ML-2C39A or ML-7211), a tuned line push-pull stage. In operation the second mixer (Figure 4) acts as a push-pull power mixer. The rf signal is impressed on the grids in push-pull: input from the second local oscillator (tripler stage) is injected on the mixer cathodes by means of an adjustable probe. The mixer output signal is fed through an adjustable probe to the cathode of the push-pull final amplifier stage.

The push-pull sections utilize a shorting bar connected directly to the radiators of the planar triode. A tunable bar connects the plate sections of the two tubes to permit tuning changes by as much as 300mc, improve the stage efficiency and broadband the stage response. The output sections of these stages are capacity coupled through a quarter wave open line. The shorted section of the line (less than $\frac{1}{4}$ wave length) appears as an inductive reactance which is of the correct amount to tune out the tube capacitance. Maximum gain bandwidth product is attained with $\frac{1}{4}$ wavelength tuning, as opposed to $\frac{3}{4}$ wavelength tuning modes.

Operating class AB, these stages draw only about 25 ma plate current per tube under no signal condition, compared to a full signal plate current of 75 ma per tube.

Where Models HTU-100 and U-HTU-100 are employed as originating transmitters, the 50% reserve power as required by the Federal Communications Commission, is obtained through use of the ML-7211. The extra reserve capability of this large cathode planar triode provides long life and additional reliability.

Planar Triodes

Machlett planar triodes have established many years service in communications operation — fixed station[1], microwave relay[2] and mobile use[3]. Of the several tubes used in these various services the ML-2C39A has been the basic type providing long life (in excess of 10,000 hours average, depending on frequency of operation and type of operation), at low initial cost and very low cost-per-hour. Essential to this performance are the well developed manufacturing techniques devised by Machlett in over fifteen years of planar

[1]L. E. Peterson, RCA Communications, Inc., and N. C. Colby, RCA-CEP, "The Life and Times of the 2C39 in Microwave Radio Relays," *Cathode Press*, Vol. 15, No. 1, 1958.

[2]"Atlantic Pipeline Company: Microwave User Since 1949," *Cathode Press*, Vol. 20, No. 1, 1963.

[3]F.L. Hilton, Motorola, Inc., "460 Cycle Mobile Two-Way Communications," *Cathode Press*, Vol. 10, No. 3, 1953.

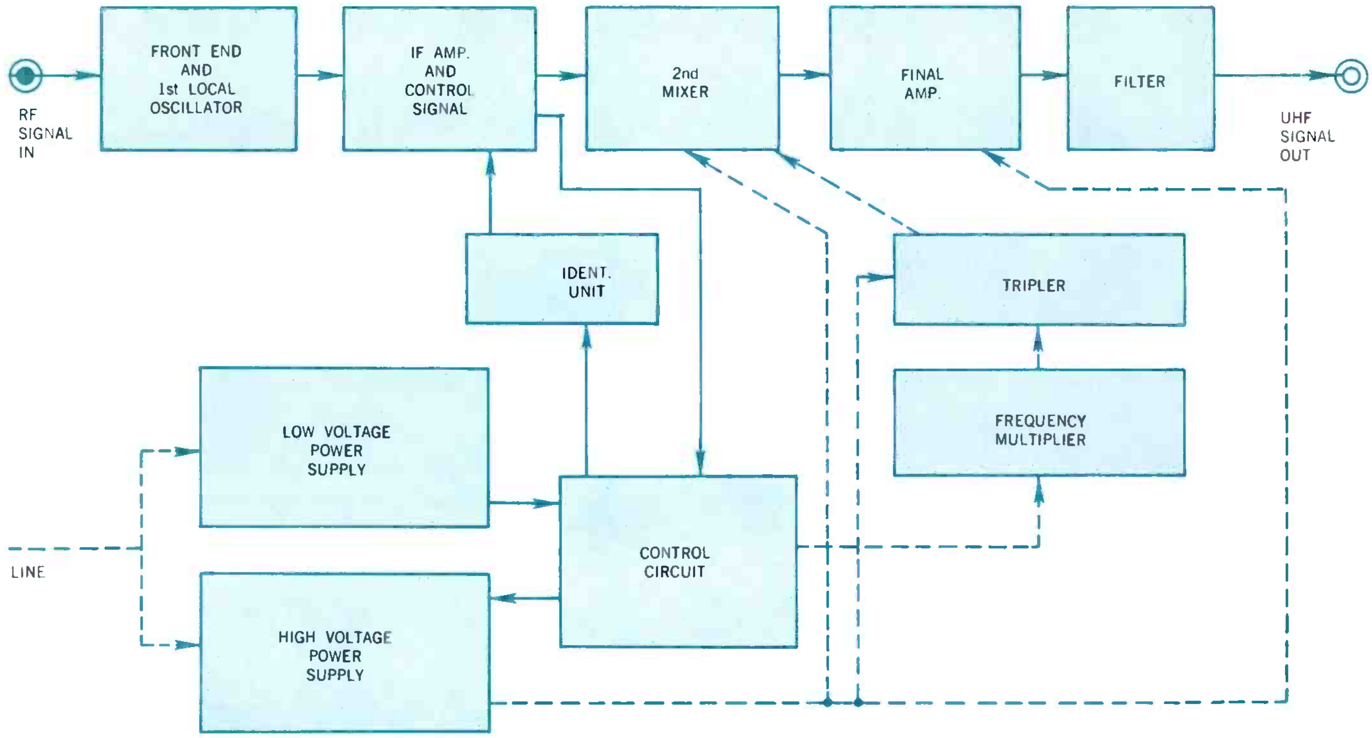


Figure 3 — Block diagram of HTU-100 Translator.

tube production. Particularly important among these techniques are those which assure the necessary planar relation of the grid to the cathode and grid to anode (both of which involve the maintenance of very close spacings at high temperature) and of the cathode processing (essential for the sustained emission of electrons at high densities).

ML-2C39A was the first planar triode to employ the rugged kovar-to-glass seals and the gold plated tungsten mesh grid. It was the first electron tube to be accepted by the U. S. Signal Corps for its RIQAP (Reduced Inspection Quality Approval Program)[4]. More recently Machlett has developed many other specialized planar triodes, including ceramic types. One of these newer types is the ML-7211, a large-cathode tube. The ML-7211 operates under the same electrical conditions as the ML-2C39A, yet is capable of a cathode current of 190 ma, as against 125 ma. (ML-7211 requires an increase in heater power: 6.3v, 1.3a, vs. 6.0v, 1.0a). An increase in output power of as much as 150% may be effected through use of the ML-7211.

As in other fields of broadcasting — television, SSB communications, AM and FM — Machlett electron tubes are to be found providing effective service, together with reliable performance. The use of Machlett planar triodes in Translators extends, to still new regions, the broad scope of application of the Machlett product.

• • •

[4]"A New Approach to Product Evaluation: RIQAP," *Cathode Press*, Vol. 11, No. 2, 1954.

ML-7211

The ML-7211 is a ruggedized, high-mu, planar triode of ceramic and metal construction designed specifically for use as an oscillator frequency multiplier or amplifier in radio transmitting service at frequencies up to 2500 Mc.

Features of this tube include low interelectrode capacitance, high transconductance, high cathode current capability and great mechanical strength.

General Electrical Characteristics

Heater Voltage	6.3 volts (nominal)
Heater Current	1.3 amperes
Mu	80

Maximum Ratings
RF Amplifier and Oscillator

DC Plate Voltage	1000 volts*
DC Grid Voltage	— 150 volts
DC Cathode Current	190 mA
DC Grid Current	45 mA

***Note:** In the Electronic Missiles and Communications Translators a maximum figure of 1250 volts dc has been authorized. The Engineering Department of The Machlett Laboratories is always available to discuss special ratings for tubes known to be operated under specific, controlled conditions.

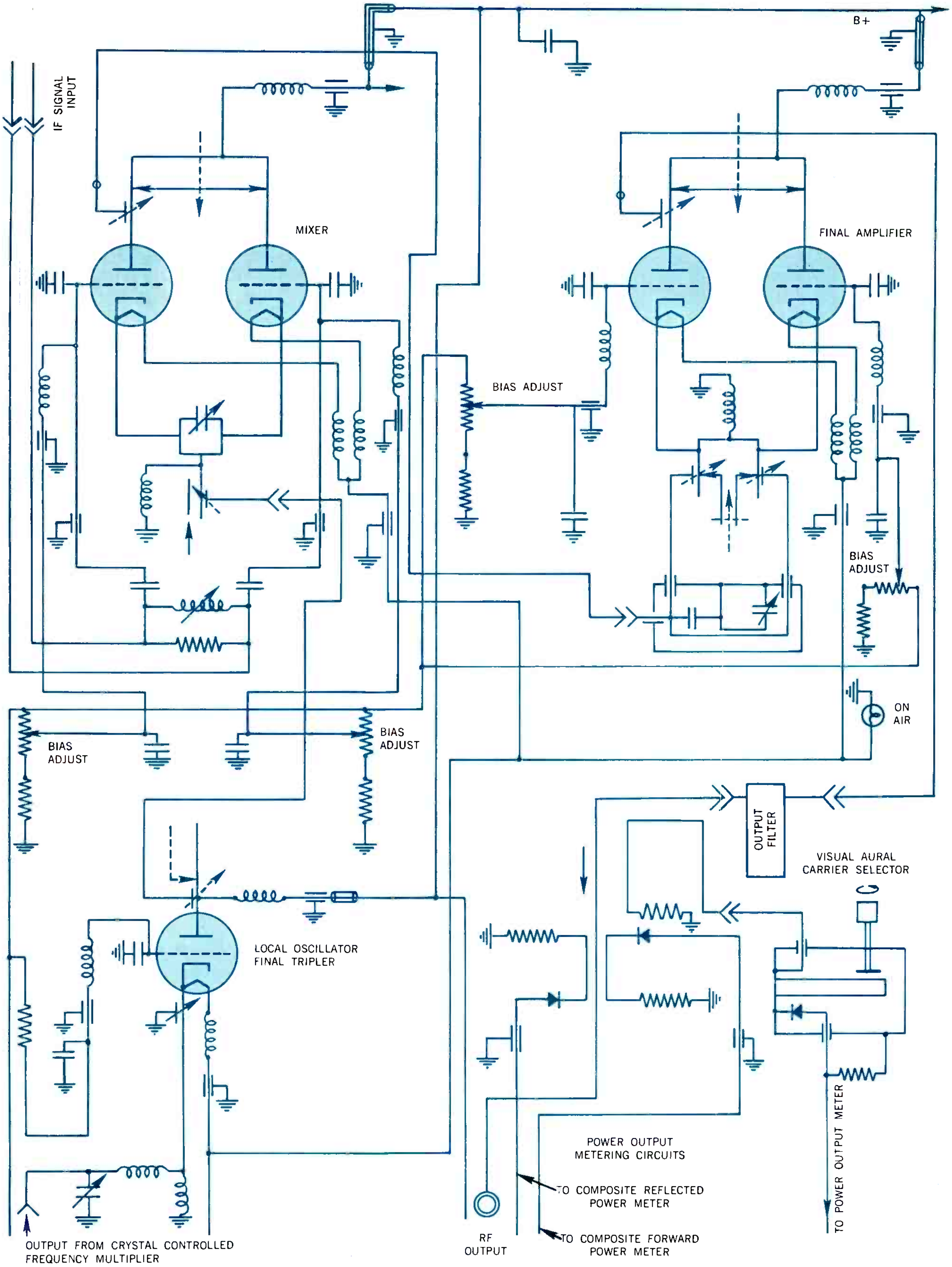


Figure 4 — Circuit detail, mixer, tripler and final amplifier stages.

by DR. H. D. DOOLITTLE,
Manager, Technology,
The Machlett Laboratories, Inc.

High Voltage Breakdown Problems in High Power Vacuum Tubes

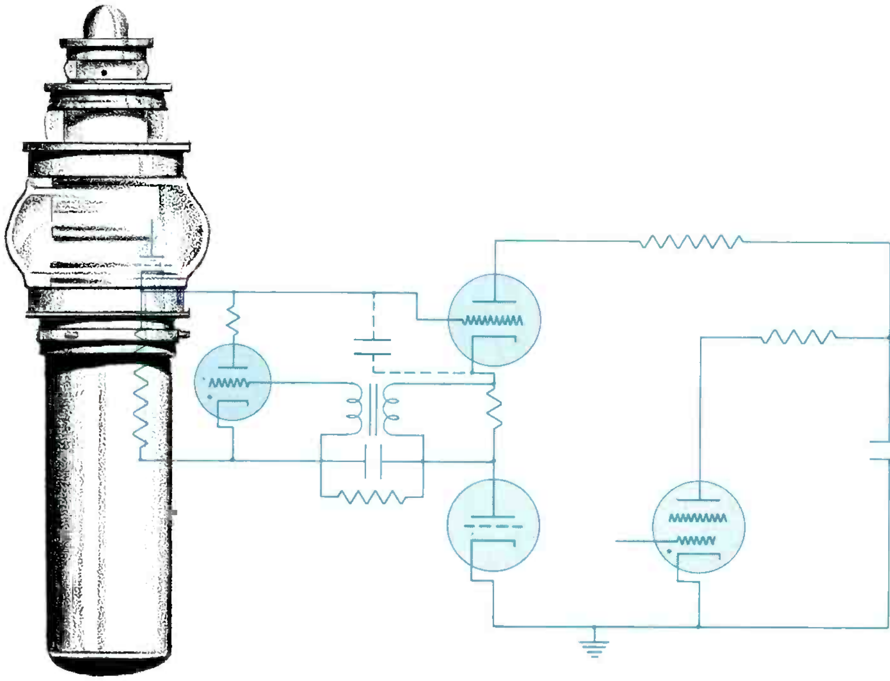
Internal flash arcs in power tubes date from the first use of high power communication transmitters at Rocky Point, Long Island. This phenomenon came to be known as the "Rocky Point" effect and has been discussed in various papers. Improved processing of tubes and better tube design have resulted in improved high voltage transmitter tube stability. The introduction of the energy diverter or crowbar, as well as other circuit improvements, has also resulted in substantial improvement in high voltage stability of power tubes. The present article describes briefly the design limitations on electron tube spacings and then discusses a number of circuit-induced instabilities with particular reference to pulse modulator tubes.

Introduction

The study of high vacuum insulation has been the subject of a great many papers (Ref. 1, 2, 3, 4) but the cause of high voltage breakdown is not fully understood. It is a complex phenomenon involving several mechanisms. The gas level in a tube is only a secondary consideration in breakdown problems. Tubes have shown good stability with gas levels above 10^{-6} torr, whereas tubes of the same type have shown poor stability with gas level below 10^{-8} torr. At one time it was thought that high vacuum insulation would cure itself after an arc. This fact is only true if the energy dissipated in the vacuum arc is small enough. With high power and low source impedance rectifiers too much energy can be dissipated in a vacuum arc to permit self-healing. Such high power arcs will produce momentary high gas pressure and also vaporize metal from the electrodes in the tube. This vaporized metal will condense on the electrodes, and, since this material is loosely bound to the electrodes, it will act as emission points for additional vacuum arcs. If the energy dissipated in a tube exceeds a few joules, holes may be melted in grids or filaments with resulting catastrophic damage.

A similar situation results with sphere gaps in air. If a pair of sphere gaps has a megohm impedance in the lead to each ball, the sphere gap may be used as a voltage measuring device. If a large amount of energy is allowed to discharge between the balls of a sphere gap (series resistance in the leads very low), an appreciable etching or even surface melting of the balls will occur. Furthermore, the voltage breakdown between the balls will be lowered for subsequent arcs.

The use of a crowbar (Ref. 5) which will act in less than 10 microseconds to divert the energy from a flash arcing tube to a shunt circuit has been of tremendous value in maintaining the high voltage stability of power tubes. This energy diverter must, in general, be a gaseous device such as an ignitron, thyratron or spark gap, so that its internal impedance can be low enough to transfer the arc from the



power tube to the crowbar circuit. The diverter circuit must also be capable of dissipating the power fed through until the primary circuit is opened. It should be borne in mind that crowbars are essential for good high voltage tube stability even when flash arcs are too weak to cause catastrophic damage.

In high power transmitters flash arcing in tubes can be caused by over-volting induced by circuit malfunction. In general, a good crowbar circuit will protect the tube from such occasional irregularities. An understanding of the types of malfunction which can occur aids the circuit designer in producing a good, stable transmitter.

Vacuum Insulation in Power Tube Design

In the design of power triodes and tetrodes the vacuum insulation between the plate and the screen grid in tetrodes, or the plate and control grid in triodes, is one of the major considerations. For stable high voltage tube operation it is necessary to have adequate spacing between these two surfaces, and the surfaces must be clean and smooth. Kilpatrick (Ref. 1) has given a curve for the maximum "spark free" potential differences between two electrodes in vacuum as a function of their spacing (Figure 1). His curve assumes parallel plane electrodes, and therefore somewhat larger electrode spacing must be used in vacuum tubes such that the increased voltage gradient at the surface of the grid wires is taken into account.

It is to be noted that the field gradients permissible in vacuum devices of large electrode areas are from 50 to 100 times smaller than would be expected from true field emission theory. This difference is due to several causes which have not been independently evaluated. Some of the sources of voltage breakdown (Ref. 2, 3, 4) within the tube are foreign atoms which lead to low work function areas, whisker growth, Schottky effect on the grids, ion exchange phenomena, photoelectric effect, and charges on insulators.

In the design of high voltage tubes it is necessary to make a compromise between tube efficiency and an ultra-conservative maximum plate voltage rating. The maximum current per square centimeter that can be drawn between the screen grid and an anode (or a control grid and anode in the case of a triode) is given by the following equation:

$$jo = \frac{2.33 \times 10^{-6} \, (ep^{1/2} + eg^{1/2})^3 \text{ amps/cm}^2}{d^2} \qquad (1)$$

where eg is replaced by Esg for tetrodes
d = grid or screen-grid to anode spacing in centimeters.

jo in this equation is the current density in amperes per square centimeter crossing the outer grid to anode spacing, and ep and eg are the instantaneous grid and plate voltages.

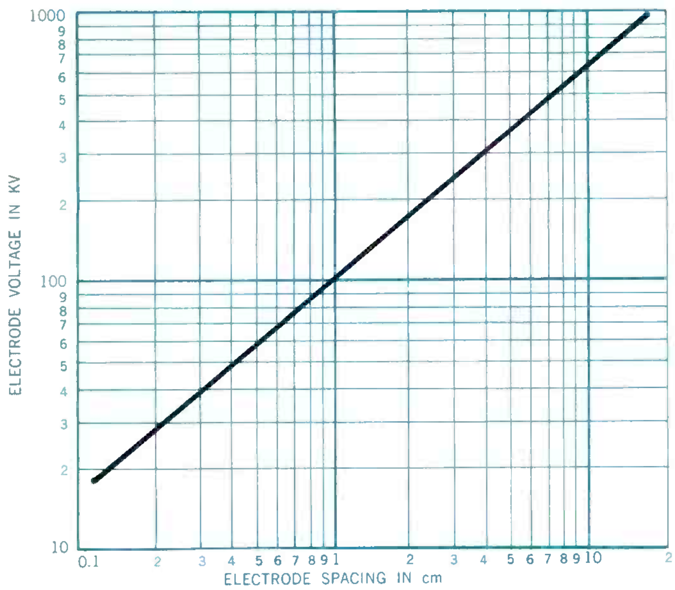


Figure 1 — Maximum "spark-free" potential differences between two parallel plan electrodes in vacuum as a function of their spacing. (Kilpatrick, **Rev. Sci. Instr.**, Oct. 1957).

The value of eg in a triode depends upon the spacing of the grid to the cathode, and is lower, the smaller the grid-cathode spacing. For any given grid-cathode spacing, eg is determined by that voltage which is necessary to give the maximum permissible cathode current emission. It is easily seen from the above equation that as the factor d is increased, ep must also be increased if eg is fixed. This means that as the outer grid to anode spacing is increased in order to increase the plate voltage rating of a tube, the tube drop will be increased somewhat faster. The tube designer must, therefore, establish a grid-anode spacing which assures good high voltage stability; but he must not over-do this spacing, since it will reduce tube efficiency.

Circuit Induced Instability

Since the tube will necessarily be designed to be as efficient as possible, it is not feasible to have a large safety factor for plate voltage. Therefore, it is essential that circuit designers pay particular attention to the maximum voltage rating for the tube. If large transients must be expected, either a higher voltage tube should be selected or suitable protective devices should be incorporated to clip transients.

The most common sources of circuit induced high voltage instabilities are:

(1) Inductive effects in the discharge circuit of pulsers.

(2) Arcing in the load.

(3) Parasitic oscillations.

(4) Line voltage surges.

In high power pulser circuits, when the current pulse is reduced to zero at the end of the pulse period, a transient voltage will be developed at the tube anode which adds to the dc plate voltage. The magnitude of this pulse will depend on the total inductance in the load circuit, the rate at which the plate current is cut off, and the anode to ground capacitance. The obvious ways of minimizing this effect are (1) to use a clipper tube, (2) to reduce the inductance to a minimum, (3) to lower the di/dt, that is, take a longer fall time. Since $\frac{1}{2}$ LI^2 is stored in the inductance of the load circuit during the pulse period, it will be necessary to dissipate this energy at the end of a pulse. In many applications, pulse switch tubes are used far below their anode dissipation capabilities, and hence, by using a slow fall time at the end of the pulse, this energy can be absorbed in the anode of the switch tube. If it is necessary to have a fast fall time, some other provision must be made to absorb this energy, such as by diode clippers.

In triodes there is an area in the static characteristics (Figure 2) where the grid current is actually negative or opposite to the normal electron current picked up by the grid during positive drive. This area of reverse grid current, which is due to secondary grid emission, normally does not cause much trouble in the operation of the tube, since the load line either does not pass through this region, or the rate of rise and fall of the grid voltage is fast enough such that the inductance in the grid circuit assures stable operation. However, when the load shorts (arcs during a pulse), the grid drive on the switch tube is at maximum value, and the plate voltage on the tube suddenly approaches or exceeds the dc power supply voltage. Under such conditions one can get what is commonly known as "pulse stretching." Due to secondary emission, the grid driver loses control of the grid potential. This results in the grid rising toward anode potential, and one of two things can happen:

(1) The grid voltage may get so high as to cause a breakdown between grid and cathode. This will cause a sudden reduction in plate current, which will produce a high peak anode voltage which often results in a breakdown over the outside of the tube before a vacuum breakdown occurs.

(2) The grid will become so positive that the secondary emission ratio of the grid becomes less than one, and the grid regains control, reducing the plate current to zero. di_p/dt may become large, and a high transient plate voltage results. A tube breakdown may then occur, or the tube may be stable after having passed a lengthened pulse.

Plate voltage have been viewed with an oscilloscope which are from two to two and a half times the dc plate voltage when the load device arcs. Similar effects happen with tetrodes when the load device arcs. Theoretically the screen grid by-pass condenser would be able to prevent the screen grid from losing control, except for the inductance in the screen grid circuit. Since these transients occur in times usually less than a microsecond, a very low lead inductance is essential to maintain control of the screen grid when a load arcs. Of course, even if the screen grid does not lose control, the $\frac{1}{2}$ LI^2 in the shorted load shows up as excessive anode voltage unless some other sink is provided to absorb this energy.

One means of protecting the switch tube from such transients is to clamp the control grid back to bias whenever the load arcs. Of course one has to take care that the plate current is not cut off too abruptly, otherwise a high transient plate voltage will show up. A thyratron in the switch tube grid circuit covered by U. S. Patent 3,069,548, and shown in Figure 3, with a proper rc time constant, has been demonstrated to be capable of shutting off switch tubes without causing excessive anode voltages. In fact, with this circuit it is possible to shut off the switch tube without using the crowbar to short the plate power supply when the load device fails.

Power tubes used in CW power amplifiers or oscillators will also be subject to high voltage transients and subsequent loss of vacuum insulation when arcs in the output circuit occur. Although 30 kV/cm is considered to be the dielectric strength of air for parallel plane electrodes, a large safety factor must be used. High voltage circuit components collect dust, oxidize and otherwise become contaminated such that breakdowns can occur at field gradients of a few kV/cm.

Parasitic oscillations can also induce over-volting of circuit components with resultant application of high transient voltages at the tube electrodes. Oscillations of this type are due to energy coupled from some part of the output circuit to an input circuit. The only way of preventing parasitic oscillations is to locate the circuits causing the trouble and provide damping (i.e., lower the Q) or alter the phase and/or amplitude of the feedback such that oscillations are not self-sustaining. Pretesting a circuit with a resistance load minimizes many of the causes of circuit instabilities. Final "de-bugging" with the actual load is essential. Tetrode tubes with their higher gain and low grid drive are more susceptible to oscillation problems than triodes. A suitable electrostatic shield between input and output circuits is highly desirable.

Barkhausen-Kurz (Ref. 6) type of oscillations can be a cause of trouble whenever a triode or tetrode is over driven, i.e., driven close to or beyond the diode line. Figure 4 shows the static data for a high-voltage tetrode using lines of constant grid drive voltage. It is to be noted that at low plate voltage, i.e., to the left of the line marked $i = K e_p^{3/2}$, the current from the cathode due to the grid drive and screen

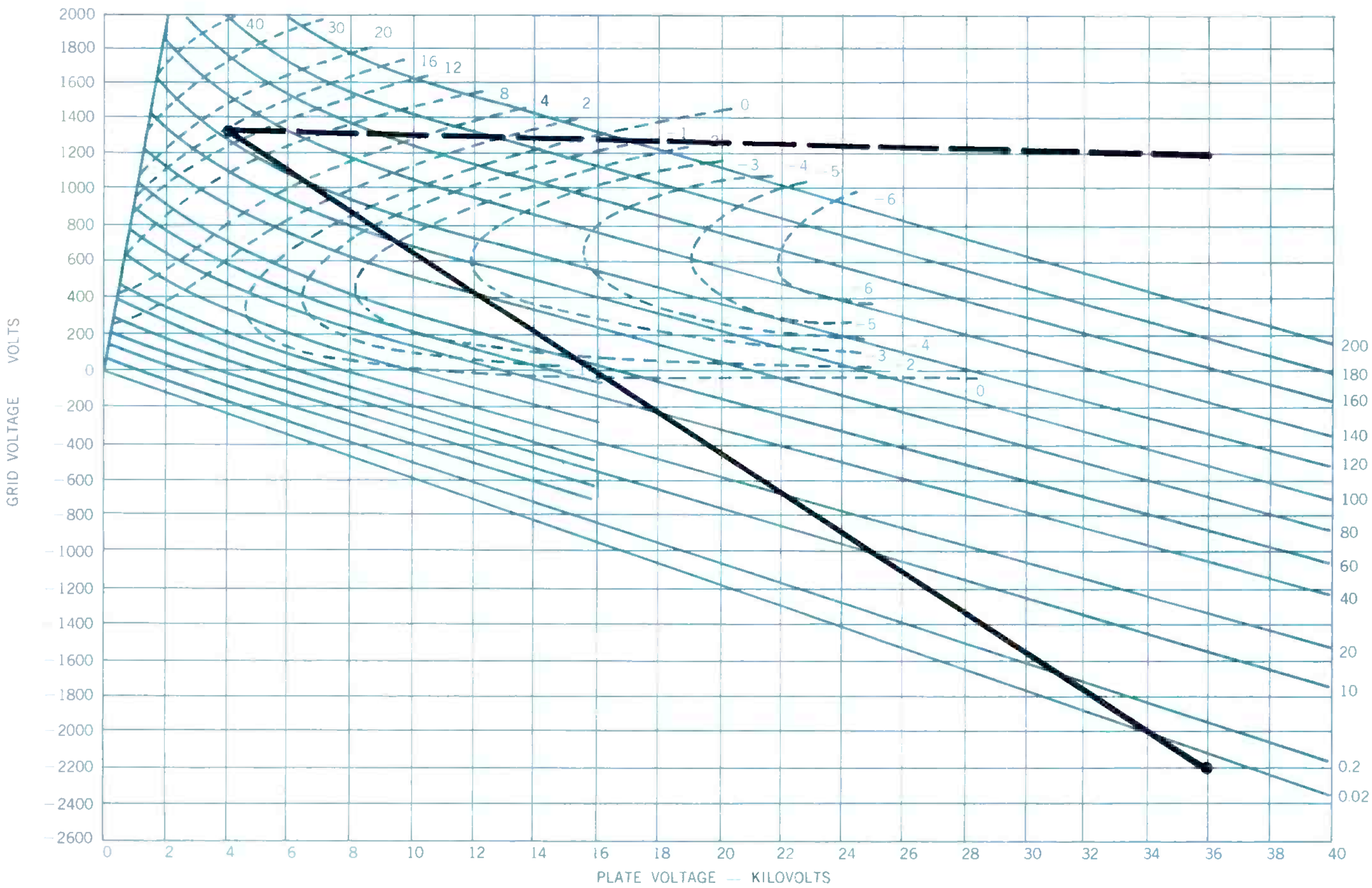


Figure 2 — ML-6696 Constant Current Characteristics showing normal load line as solid line, and load line when load arcs as dotted line.

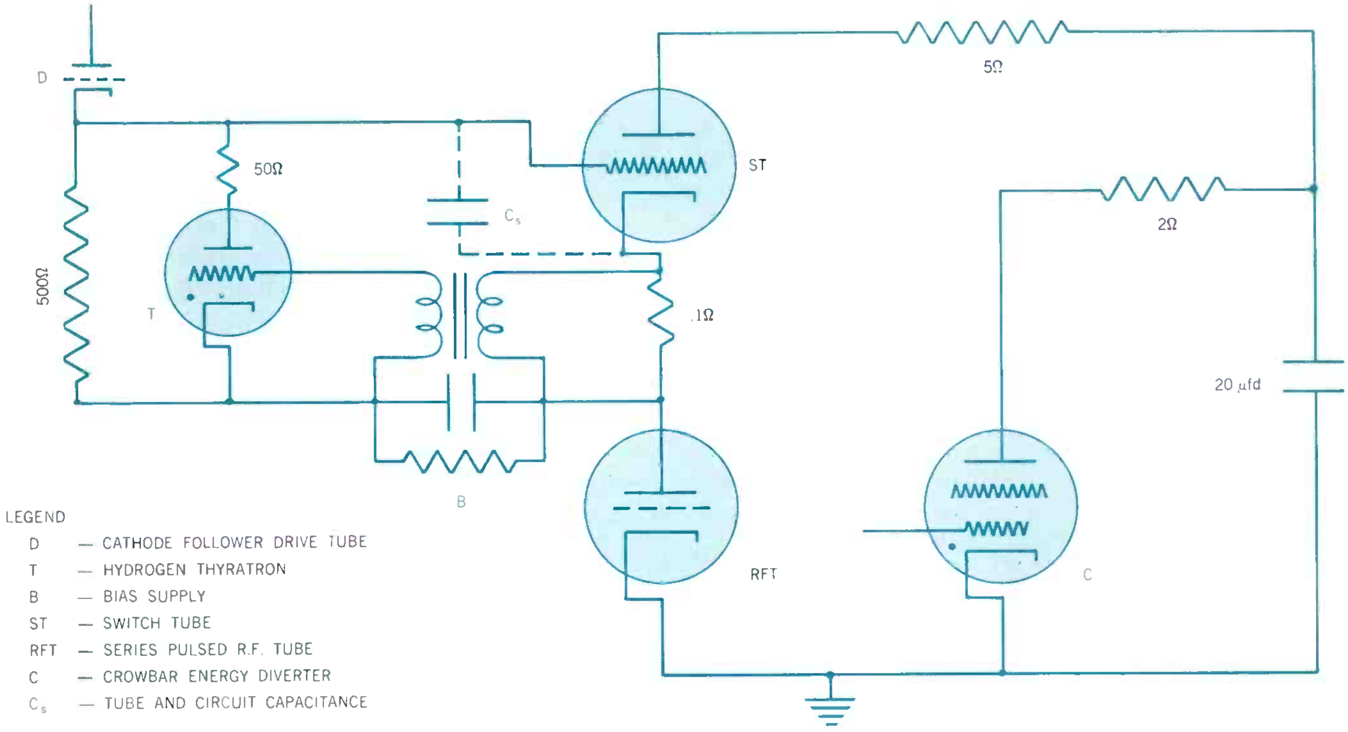


Figure 3 — Circuit showing a thyratron in a switch tube grid circuit. The switch tube is cut off when load tube arcs by firing the thyratron, T, by voltage developed across 0.1 ohm resistor.

grid voltage of 1000 volts cannot arrive at the plate but ends up on the screen grid or control grid. Equation 1 gives the maximum current which can arrive at the anode for a given plate and screen grid voltage. With the latter fixed, the current to the plate must decrease as the plate voltage is decreased. Actually a virtual cathode is formed between the screen grid and anode. Electrons passing the screen grid return to the screen grid and may oscillate about the screen grid several times before being collected by the screen grid. This oscillation is a transit time type of oscillation and is a function of tube geometry and applied voltages. Its amplitude and frequency are affected by the external tube circuitry. The power involved is usually quite small, but it may be enough to cause trouble, particularly if other circuitry is resonant at the same frequency. The practice of applying full drive power and then raising the anode voltage is conducive to troubles of this sort, since one runs through the complete gamut of plate and grid voltages in the Barkenhausen-Kurz region.

Line voltage surges can occur due to various causes. In induction and dielectric heating equipment where filter chokes and condensers are often omitted, a starting transient of nearly double the dc power supply voltage can occur if the full plate voltage is applied by the snap of a switch. The magnitude of the over-voltage depends on the instantaneous phase of the line voltage at the time the primary contacts are closed and also on the loading of the oscillator. To control starting transients, a load on the secondary of the transformer which opens in a few seconds after closing the primary contactor is usually sufficient.

In power amplifiers or pulsers using well filtered power supplies, there should be no such transients. At high power levels it is advisable to use induction regulators so that the voltage may be raised slowly from half to full power. If voltage must be snapped on instantaneously, it is advisable to provide half-voltage taps so that a new tube can be run for a while at reduced voltage and power. Similarly, a dropping resistor in the line that will permit coming on at 80%-90% of plate voltage is very helpful in aging a new tube. This resistance can be shorted out after a few minutes to provide full power.

Overall Tube Protection

It has been shown that a few joules can cause permanent tube damage. Contrary-wise, 500-1000 joules may cause no permanent damage. When a tube is over-volted, it is difficult to predict the course of an arc. Either sufficient series resistance must be included in the plate supply lead or a crowbar must be used, or both. At power levels above 100 KW it is essential to use fast crowbars (Ref. 5) to divert the stored energy in the circuit from discharging through the power or switch tube. It is also necessary to use

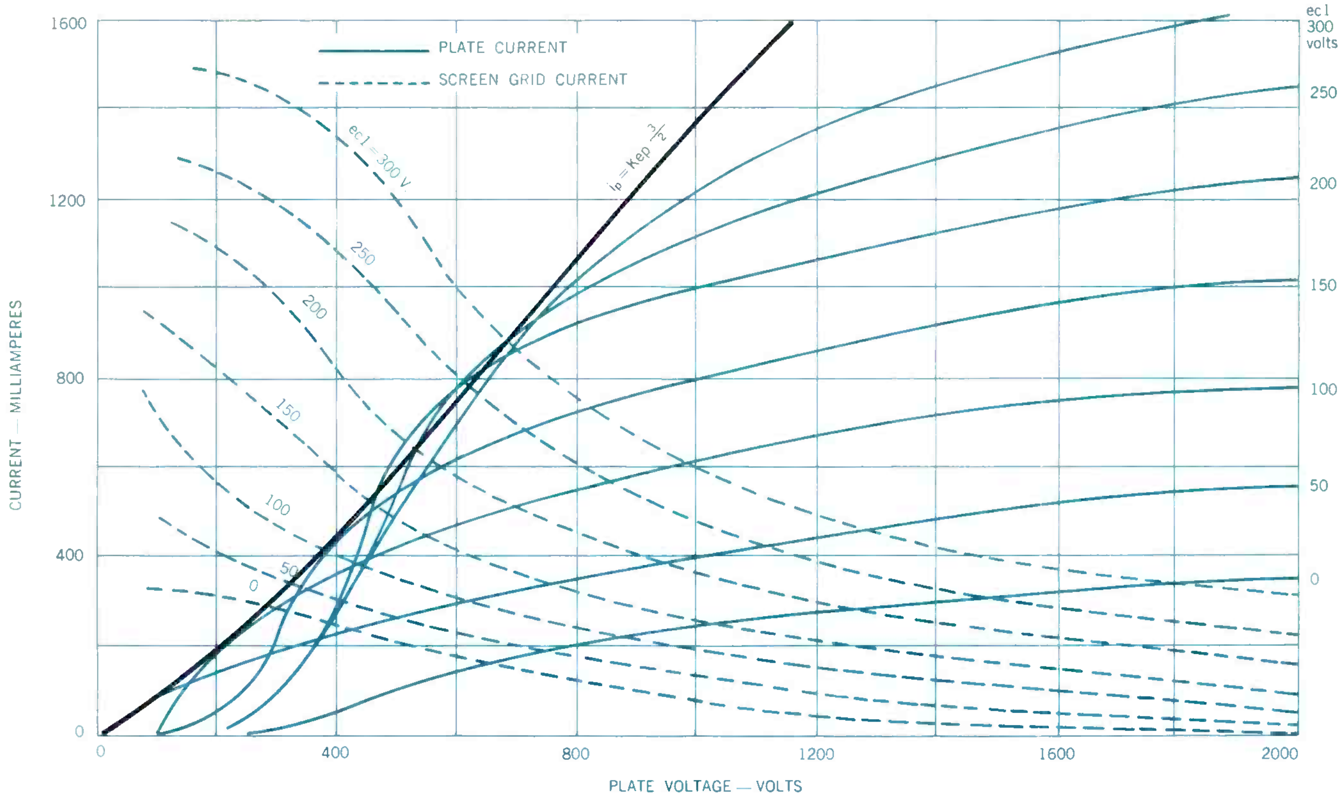


Figure 4 — Typical Constant Grid Voltage Characteristics. Line labelled $i_p = Ke_p^{3/2}$ shows plate current drawn from virtual cathode formed between screen grid and plate.

fast circuit-breakers, since once the crowbar fires, energy will be fed in from the lines until the primary contactor is opened. The design of the crowbar circuitry must be such that the discharge circuit through the crowbar is critically damped. If the inductance in the crowbar discharge circuit resonates with the filter capacitor, and the losses in the circuit are small, the stored energy will not be dissipated, but the charge on the condenser will be reversed. The power tube may then dump this energy with damage to itself.

In addition to using a critically damped crowbar circuit, some protection is necessary to make sure that the filter condenser does not recharge again after the condenser has been dumped and the crowbar de-ionizes. In other words, it may be necessary to fire the crowbar several times until the main contactor is open.

In one 200 KW output dielectric heating equipment where a tube was arcing several times a day, the installation of a crowbar circuit allowed the same tube to operate for over two months before a kickout occurred. In this case, the energy dumped in the tube prior to installation of a crowbar was enough to vaporize metal within the tube, causing high susceptivity to additional flash arcing; but, there was not enough energy to cause permanent or catastrophic tube damage. The installation of the crowbar circuits kept the dissipated energy in the power tube low enough to allow the tube to remain stable.

Flash arcing in tubes with ratings of less than 100 kVdc should not be a major cause of voltage instability. Properly designed tubes used in circuits with adequate protective devices should not break down under voltage of their own accord. When new tubes are installed in a circuit for the first time, some seasoning can be expected, but in general the tubes should run stably after the first few hours of operation. There are so few equipments in the field today using tubes with voltage ratings above 100 kVdc that it is not possible to say whether long stable operation can be expected at high voltages or whether some new phenomena may appear.

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ML-7210[2]	3Gc	3500 v eb 2 8 a ib	—	—
ML-7698[3]	3Gc	3500 v eb 5 0 a ib	3Gc	2000 Vdc Eb 5 0 a ib
ML-7815[1, 4]	3Gc	3500 v eb 3 0 a ib	3Gc	2000 Vdc Eb 3 0 a ib
ML-7855[1, 4, 5]	3Gc	3500 v eb 3 0 a ib	3Gc	2000 Vdc Eb 3 0 a ib
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