MACHLETT

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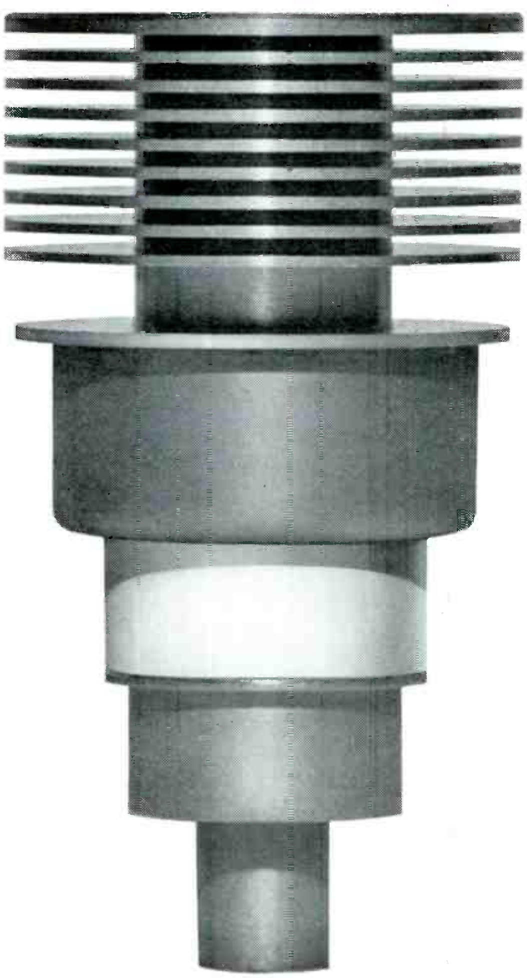
UHF

Frequency Stable

CW or Plate-Pulsed

ML-7855



Special anode design of ML-7855 permits frequency stable operation within 10-15 seconds after application of high voltage. (Frequency change during this initial period is within 1 mc).

ML-7855 provides frequency stable operation with unregulated supply, as change of plate dissipation has no effect on change of frequency.

CW operation to 2500 Mc, with 1000 V Ebb, 100 ma Ia.

Plate-pulsed to 3000 Mc, with 3500 v eb, 3.0 a ib, with a tp of 3 usec at 0.0025 Du.

Send for Machlett UHF Planar Tube Brochure

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MACHLETT

The Machlett Laboratories, Inc.
Springdale, Connecticut

CATHODE PRESS

Vol. 19, No. 1, 1962

Editor, *Richard N. Rose*

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IN THIS ISSUE

Cathode Press reports developments of interest to the Electronic Industry at large through its coverage of the latest advances in the design, manufacture and use of electron tubes — with specific reference to their use for x-ray, communication and industrial purposes. Particular emphasis is placed on the role of The Machlett Laboratories in the development of new electron tube products, improvement in current types and in their application.

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AUGUST 1962

Development of a Hard Tube for High Power Pulse Switching at 180 kV

Introduction

The commercial market contains a number of power tubes capable of emission in the order of hundreds of amperes. In the development of new tubes for pulse generator service, therefore, most of the emphasis at Machlett has been on designs for higher voltage. Operation of tubes in parallel, moreover, has been generally more satisfactory than series stacking, so there has been more incentive to work towards higher hold-off voltage capability in a single device.

The DP-18 has been developed to operate at dc hold-off voltages up to 180 kV. The thoriated-tungsten filamentary cathode has been conservatively designed to provide at least 225 amperes pulse cathode current. Through careful design of the active electrode geometry, the DP-18 is able to switch 20 megawatts of pulse power at a plate efficiency of nearly 90 per cent and with less than 50 amperes pulse drive current. Ample electrode dissipation capability permits full power operation at duty factors up to 0.005 and higher, unless there is appreciable power dissipated in the anode due to stray capacitance charging at high pulse repetition rates.

by C. V. WEDEN, Product Engineer, The Machlett Laboratories, Inc.

Electrode Design

The electrode geometry of the DP-18 is that of a high-mu triode. The cathode, as mentioned above, is thoriated-tungsten, in a self-supporting filamentary structure. Cathode heating characteristics are 11.5 volts, 360 amperes. This choice of emitter was made because of a desire for long life, high plate efficiency, and long pulse duration.

Plate efficiency is a consequence of grid-anode spacing: the closer the spacing, the lower the tube drop and the higher the efficiency at a given dc plate voltage. It has been found that tubes with metallic cathodes will support field gradients in the grid-anode region about twice as high as tubes with oxide cathodes. With a thoriated-tungsten cathode, therefore, a closer spacing can be tolerated, resulting in higher efficiency.

The pulse duration with metallic cathodes of this type is restricted only by electrode temperatures. Grid dissipation is usually the limiting factor due to its relatively low thermal time constant. In general, pulse durations of several milliseconds can be handled, longer at lower peak power.

The grid has been designed as a compromise between low field gradient and low screening fraction. Special surface treatment based on the emission-inhibiting properties of platinum results in low thermionic grid emission. The overall tube design, furthermore, results in a favorably low yield of secondary grid emission to the extent that negative grid current is virtually eliminated. This is an important feature, since an arc in the load tube puts the power supply voltage on the switch tube when its grid is probably at a high positive voltage. Under these conditions many triodes and tetrodes exhibit negative grid current due to secondary grid emission, in which case the grid loses control unless compensation is provided in the circuitry.

The anode is a high-density copper forging. Longitudinal fins are machined on the exterior to provide sufficient heat transfer area to circulating oil.

Shielding and Envelope Design

One of the most important considerations in high-voltage tube development is proper design of the envelope insulator. The glass or ceramic must be shielded from direct filament radiation, and the shields themselves — and electrode supporting members — must not be sources of field emission. In Figure 1 the internal shields can clearly be seen through the glass bulb. The negative electrode terminal (grid or cathode, as the case may be) is covered by a smooth external shield. This combination puts the glass-metal seal in a virtually field-free region, thereby minimizing the chance of electron emission from this negative junction.

Regarding the choice of insulator, Machlett Laboratories is presently investigating several glasses and high-alumina ceramics. At this point it is impossible to say that any one material is clearly superior to all others. In the size necessary for the DP-18 (nominally 16 inches in diameter, 13 inches in length), glass required a much shorter lead time for delivery, and it simplified fabrication of the mating kovar collars.

Anode Cooling

The tube is designed to be immersed in mineral oil or equivalent dielectric medium during operation. The anode is designed for cooling by a forced flow of the insulating oil upwards over the anode surface. This surface has been extended by the formation of 240 fins approximately 1 mm thick, 5 mm deep, and 2 mm apart. The fins can be seen in

Figure 1 — Machlett DP-18 high vacuum high power pulse switching tube with anode jacket removed.

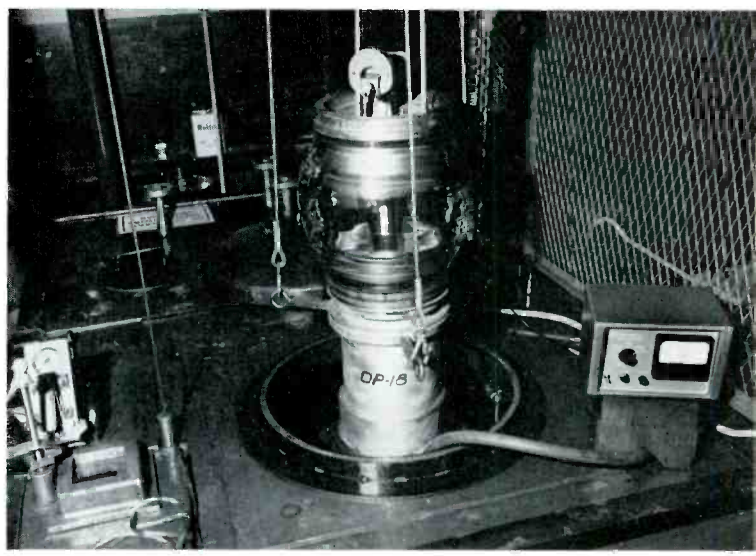


Figure 2 — The DP-18 is shown here being lowered into the Machlett 200 kV, 200 mA hard pulse modulator test facility.

Figure 1.

In operation a close fitting jacket is attached to the anode, and cooling oil is forced through the channels formed between fin pairs. The circulating oil typically enters coaxially at the bottom and discharges near the top of the anode into the bulk oil in the high-voltage tank. Figure 2 shows the tube, with cooling jacket attached, being lowered into the Machlett 200 kV modulator test set (described in another article). While *most* of the heated oil discharges directly into the tank, some of it passes through the large holes in the lifting flange to cool the anode seal and bulb. In addition, a small flow of oil is promoted in the grid-cathode terminal region to cool these seals.

Operation

DP-18 tubes have been operated into a 1000-ohm resistive load at hold-off voltages up to 180 kV and pulse plate currents up to 150 amperes. In a typical test these conditions were obtained at pulse durations of 3-5 microseconds and 200 mA average plate current, which is the rating of the test equipment.

Plate leakage current (field emission) averages well under 1 mA at 180 kV. High voltage stability at 180 kV has been checked by operating the tube with a series resistance as low as 125 ohms.

For bringing this development of a 180 kV switch tube to successful realization, credit is due to Helmut Langer, Development Engineer, and to Barry Singer, Mathematician, working under the direction of Dr. H. D. Doolittle.

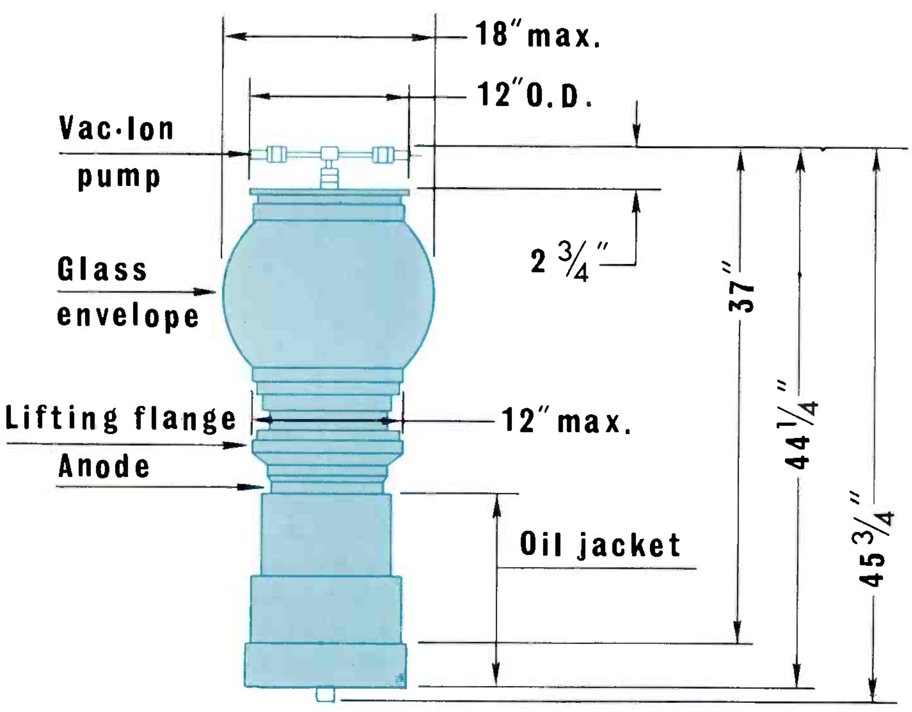
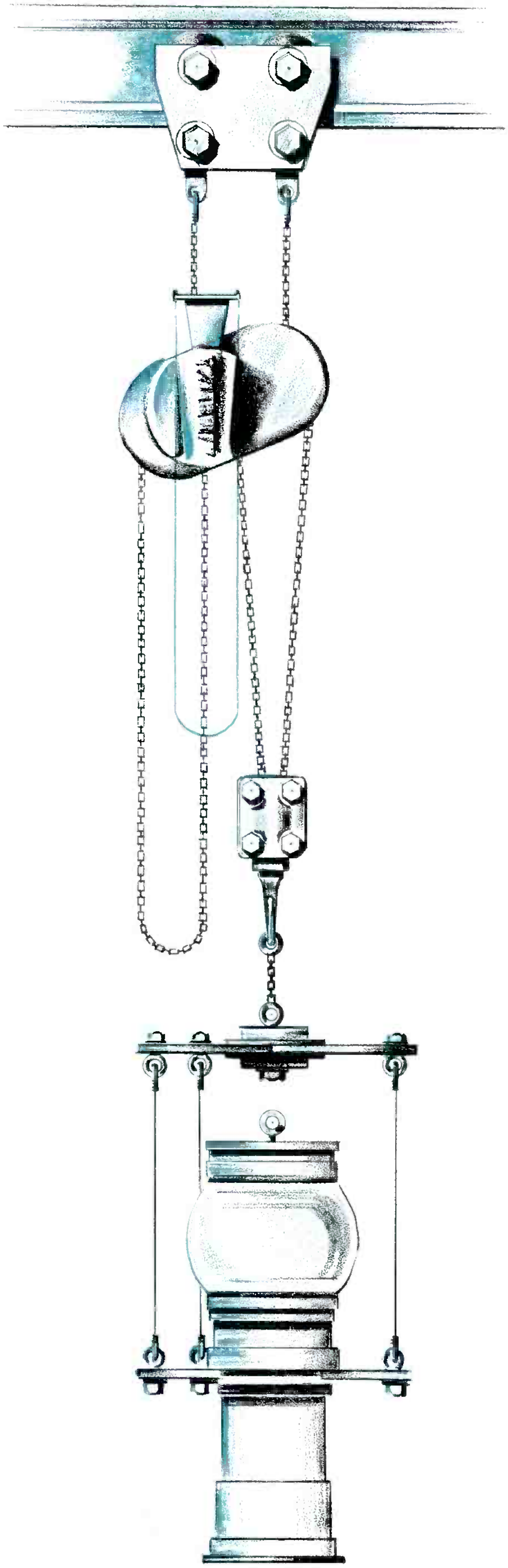


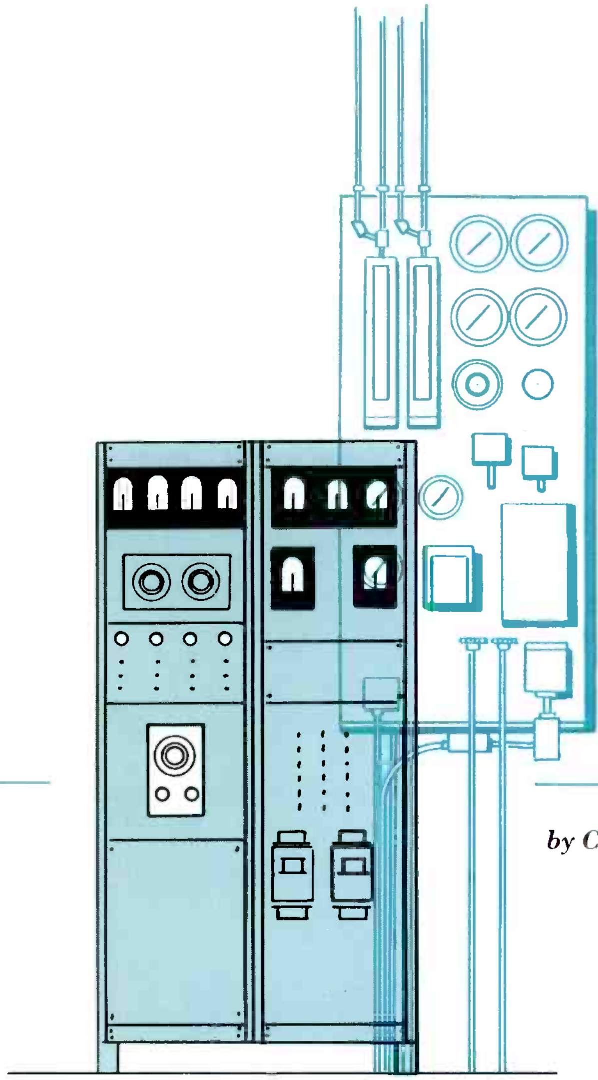
Figure 3 — Outline dimensions DP-18.



Hard Pulse Modulator Test Facility: 200 kV, 200 mA Capability

Editor's Note

During the past six years The Machlett Laboratories has been active in the development of two lines of vacuum tubes specifically designed for pulse modulator service. A series of oxide-cathode shielded-grid triodes has been developed for operation up to 75 kVdc and 5 megawatts pulse switching power. In addition, thoriated-tungsten filament triodes have been developed for operation up to 200 kV hold-off and 20 Mw pulse power. Development is continuing to extend the range of oxide-cathode tubes to 200 kV, and thoriated-tungsten tubes to 400 kV. An important part of this development program has been the design and construction of an engineering facility with provision for making simulated operational tests on these high power, high voltage tubes. A 200 kV, 40-kilowatt average power pulse test set, the subject of the following article, is now engaged in testing a broad spectrum of Machlett switch tubes.



by C. V. WEDEN, Product Engineer, The Machlett Laboratories, Inc.

The importance of operational test equipment in the evaluation of pulse modulator tubes cannot be overemphasized. Static end-of-load-line checks are essential to monitor electrode spacings, and high-voltage hold-off testing is a useful preliminary in the aging schedule. But to be assured that a tube will do the job for which it is designed, it is necessary to test it under operating conditions. Ideally, this means using the tube in a modulator to deliver pulse power to a typical load tube, i.e., magnetron, amplitron, klystron, etc. The cost of simulation to this degree at high power levels would be unwarranted, but a reasonable compromise is to use a resistive dummy load. The important point is to check high-voltage stability of the modulator tube under operating conditions preferably somewhat beyond the required hold-off voltage, pulse current, and stored energy. Experience has shown that the static hold-off capability of a tube does not permit one to predict its performance under normal drive conditions.

A general view of the 200 kV test facility is shown in Figure 1, and a simplified circuit diagram is shown in Figure 2. The diagram also shows the relative physical layout of the major components. The main high-voltage oil tank is divided into quadrants, housing (1) the tube under test, (2) the plate voltage supply, (3) the storage capacitor bank, and (4) the load resistor bank. The pulse driver and control circuitry are housed in the adjacent cabinets.

The tank is half below grade level, providing head room for hoisting heavy tubes into position and simplifying the x-ray shielding. The hoist is arranged so that it serves also to lift the major high-voltage components out of the tank for maintenance.

High-Voltage Power Supply

The dc plate power supply has been designed conservatively for continuous operation at 200 kV, 200 mA. To date the equipment has been limited to operation at 180-185 kV by the specially selected and aged ML-6908 rectifiers. This type is normally rated for 150 kV peak inverse voltage. A set of modified ML-6908's is being built which will permit operation at the full 200 kV in the near future. A standard three-phase, full-wave rectifier circuit is used.

The energy storage capacitance is made up of two 0.5-μf banks in series, giving a total capacitance of 0.25 μf. Each bank consists of five 0.1-μf, 125 kV units connected in parallel.

Load Resistors

A series-parallel bank of resistors is mounted in the oil tank with manual switching accessible above the cover. Load resistance of 250, 500, 750, 1000, 5000, or 40,000 ohms may be selected. In addition, a direct connection (zero load) is available for making static end-of-load-line and current-division checks.

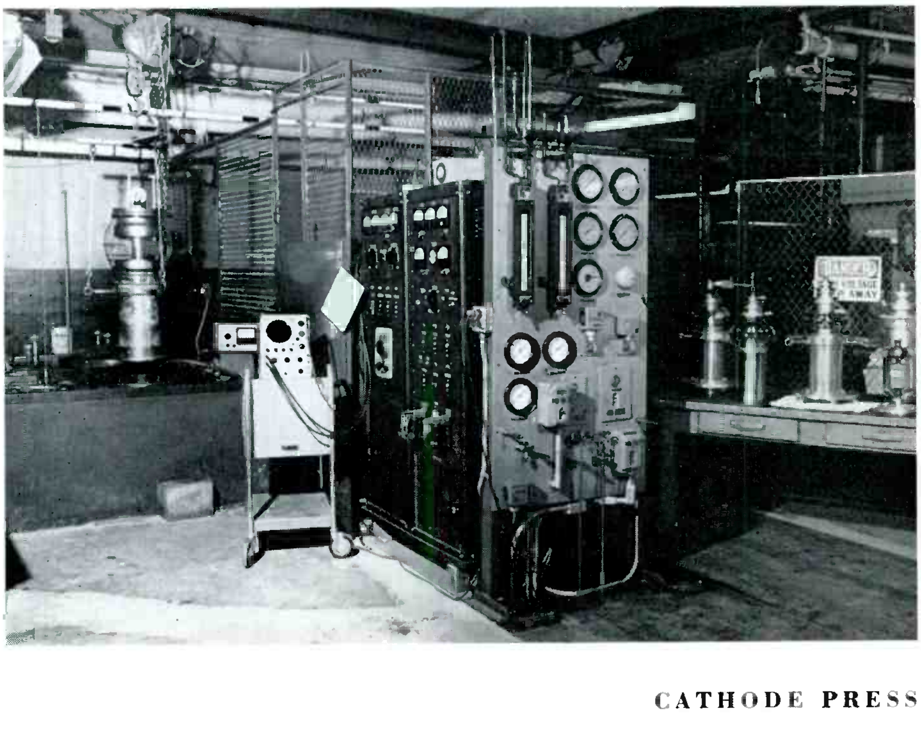
Tube Under Test Compartment

The tube under test is connected to a socket which is mounted on an elevating platform. A close-up of the tube under test quadrant is shown in Figure 3, wherein a developmental 180 kV switch tube, type DP-18, is being installed.

The operator may raise the platform to a convenient height with a hand crank, and place the tube in its socket. For tubes requiring a forced flow of oil over the anode, the tube is automatically connected to the high-pressure oil supply line. (The oil systems will be described later in some detail.) Electrode connections can be made at convenient levels before the tube is completely immersed in the oil.

During operation, the tube may be observed through the lead-glass port by manipulating a submerged mirror. The observation port is shown in Figure 3 just to the left of the tube, and the mirror adjusting rod is immediately to the left

Figure 1 — General view of 200 kV test facility.



of the port.

The single-phase, ac filament supply is capable of providing up to 20 volts and 500 amperes.

Monitoring jacks are provided for viewing the pulse plate current (up to 500 a), grid drive current (up to 100 a), and grid drive voltage (from bias level up to 3000 volts positive, for a typical switch tube).

Pulse Driver

The tube under test is driven by a hard tube modulator using the ML-6544 shielded-grid triode. The pulse duration is variable from 1- to 10-microseconds, and the pulse repetition rate can be varied from 20- to 5000-pulses per second. A view of the driver cubicle with access panel removed is shown in Figure 4. The ML-6544 is at left center on the ceramic support, connected by flexible duct to a blower. At the upper right is an air cooled dummy load used in making preliminary adjustments on the driver. The ML-6544 is driven by a standard pulse generator and amplifier stages.

Cooling and Filtering Systems

The tank is approximately 9 x 15 x 6 feet deep, and its capacity is some 5700 gallons. The insulating oil used is Esso Special Marcol, a high-purity, high-dielectric-strength oil, and this oil is circulated by two separate systems through an external heat exchanger and filter. The total heat load is 45 kW, divided roughly between the tube under test (22 kW total, plate dissipation plus filament power) and the load (20 kW), with the remainder charged to losses in the high voltage power supply and miscellaneous components.

A "high-pressure" pump system is used to supply a forced flow of oil to the anode of the tube under test. The flow rate can be adjusted up to 30 gpm with a back pressure up to 30 psi. The supply pipe is connected to a short flexible line which connects coaxially with the elevating platform. When a tube is placed on the platform the inlet nipple on the tube socket engages an O-ring in the platform connection, thereby coupling the tube to the high pressure oil supply. In opera-

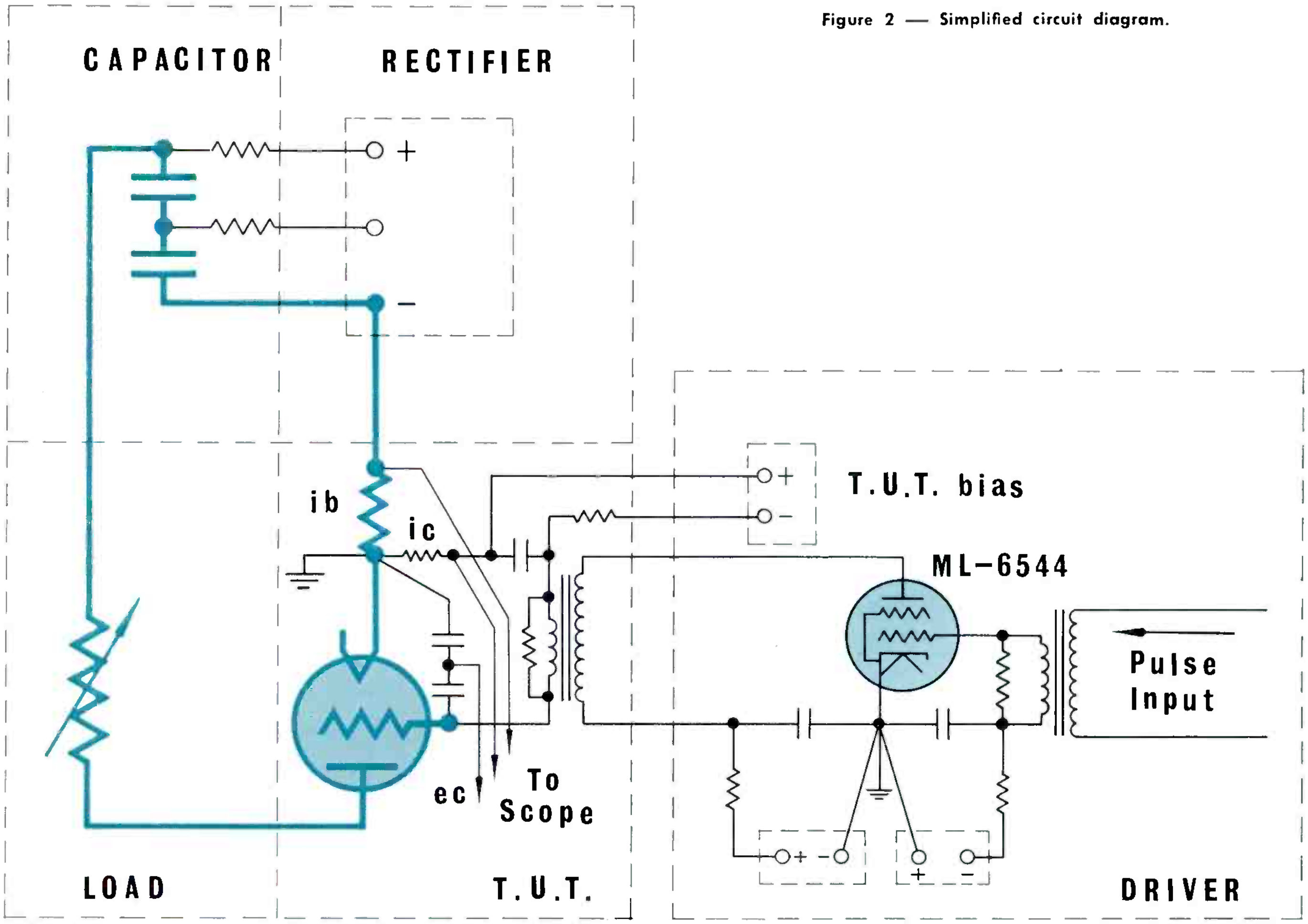


Figure 2 — Simplified circuit diagram.

tion, oil is directed upward over the anode surface, discharging into the bulk oil in the tank.

A common return system draws the heated oil through perforated pipes located just below the oil level in the tank. This system has a capacity of 100 gpm. After passing through the heat exchanger, about one-third of the cooled oil passes through a booster pump of the "high-pressure" system. The remainder flows directly to the tank where it is distributed by perforated pipes located near the bottom.

The heat exchanger is water cooled. It has been designed to maintain a mean bulk oil temperature of 38°C (100°F).

The filter system has a capacity of 15 gpm, retaining particles up to 5-10 microns and up to a pound of water. The system can be operated whether or not the test set is in use, and the total supply of oil will pass through the filter every 6½ hours.

The oil system control panel is adjacent to the driver section and is shown in the foreground of Figure 1. It has been arranged so that all switches, control valves, pressure gages, flowmeters, and the thermometers are conveniently accessible and visible to the operator.

• • •

The continued expansion of Machlett's line of high power tubes has created a need for advanced facilities to provide adequate evaluation of tubes under realistic load conditions. The extent of the Machlett capability in this field is now demonstrated not only by the breadth of pulse types available but by the depth of the supporting equipment.

The author wishes to acknowledge the contribution of the Machlett equipment engineering and construction groups in bringing this project to successful fruition; in particular, that of D. C. Kudola for the electrical layout, W. A. Bulger for the oil circulation systems, and C. A. Simpson for the overall mechanical layout and design of the tube under test mounting and handling facilities.

Figure 3 — Tube-under-test quadrant.

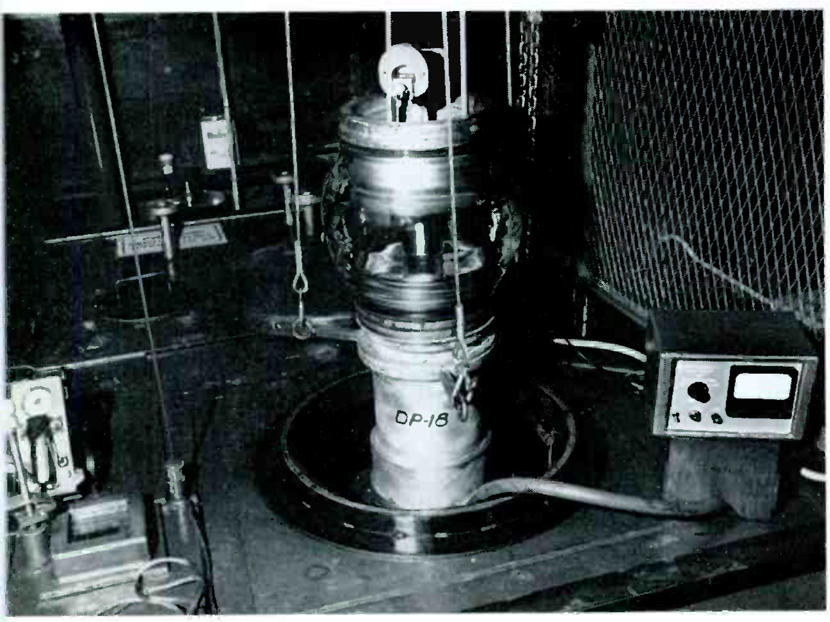
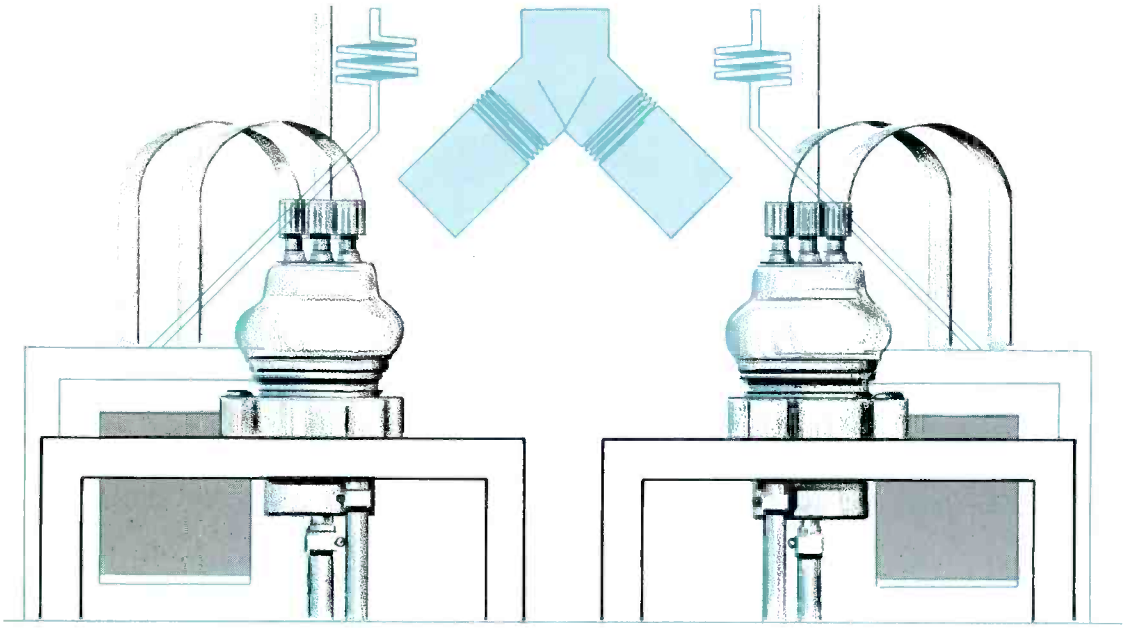


Figure 4 — Driver cubicle with access panel removed.

KGEI Converts to ML-356's



in PA and New Modulator

by DON C. SMITH, Chief Engineer, KGEI

The Far East Broadcasting Company broadcasts the Christian message of truth and freedom in 36 languages and dialects from its national and international broadcast facilities, located in the Philippines, Okinawa, and Belmont, California. Transmitter powers range from 1,000 to 100,000 watts.

The latest acquisition is 50,000-watt KGEI near Belmont, California, on the San Francisco Bay. Formerly owned by General Electric, the present schedule consists of 6 hours each evening directed to Latin America in English, Spanish, Portuguese, Chinese and Russian. The response to this programming has been gratifying, and an expanded schedule is anticipated.

The 1939 vintage G.E. transmitter utilized a pair of 880's in the rf and 893's in the modulator power amplifier. Past experience over several years indicated life averages of 3,680 and 5,800 hours respectively. The filament power consumption is quite high since both these have pure tungsten filaments. Modern thoriated-tungsten filament tubes are available which should render much longer life with lower filament power consumption for approximately the same price per tube.

Consideration was given to the possibility of converting to another type. For the rf section, the choice was obvious. The ML-356 is a thoriated-tungsten version of the 880, identical mechanically and electrically except for filament voltage and current requirements. The required filament power of the ML-356 is only 1,275 watts, less than ⅓ that of the 880.

Before ordering new filament transformers, consideration was given to what might be done to use the existing 880 transformers. Calculations and measurements of the purposely high leakage inductance and comparison of the two loads indicated the 7.5 volts at 170 amperes required for the ML-356 should be obtained by using approximately 107 volts on the transformer primary instead of the 230 volts required for the 880's. Since a combined Variac and buck-boost transformer arrangement was used for varying tube filament voltage, it was felt that the 107 volts could be obtained by feeding from 120 volts. This was cautiously tried when the first ML-356 was on hand and worked exactly as anticipated. The 880's were then

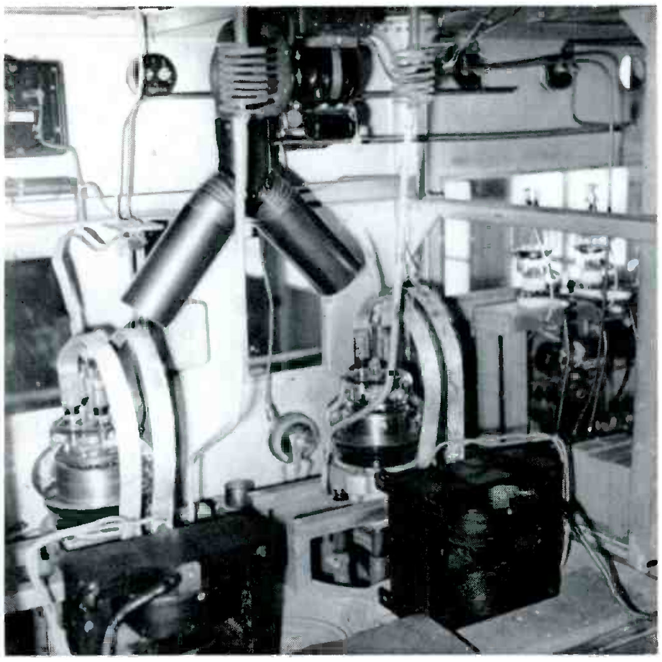
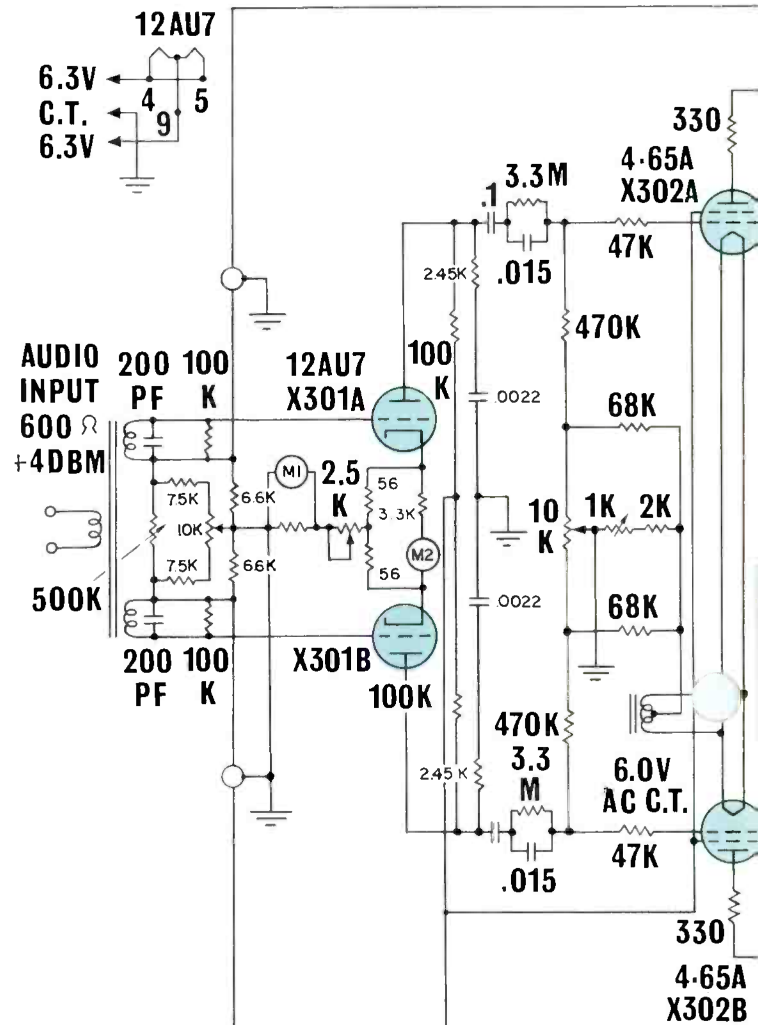


Figure 1 — Rear view of modulator showing completed conversion.

replaced one at a time when they breathed their last. There is now about 5520 hours on the oldest ML-356 with no noticeable change in characteristics. The transformer hardly heats at all, and the filament connectors run cooler. We are completely satisfied with the change.

For the modulator the change was not so simple. There is no thoriated-tungsten equivalent to the 893A available, but there was more to be gained here by conversion to a thoriated-tungsten filament tube. After considering several possibilities it was concluded that conversion to ML-356's here also would be the best solution (see Figure 1). Another problem immediately arose. The ML-356's require about 1.3 amperes each peak grid current at the required power output, whereas the 893A's require less than one ampere. The 849 drivers could not supply this in an AB₁ cathode follower circuit without a step-down transformer. This, added to the fact that the 849 is expensive for its size, nearing obsolesence and a little difficult to obtain, led to the decision to redesign and rebuild the entire electronics of the modulator using ML-356's. The existing modulation transformer and plate supplies were retained.

Type 304TL drivers were chosen because of their ability to produce the required ML-356 grid current operating class B₁ (Figure 2). It is a preferred type and the cost is about 1/3 that of the 849. Table I shows an operating cost comparison of the old and the new. Experience reported from ML-356's used in similar transmitters indicates an average life of at least 10,000 hours can be expected.

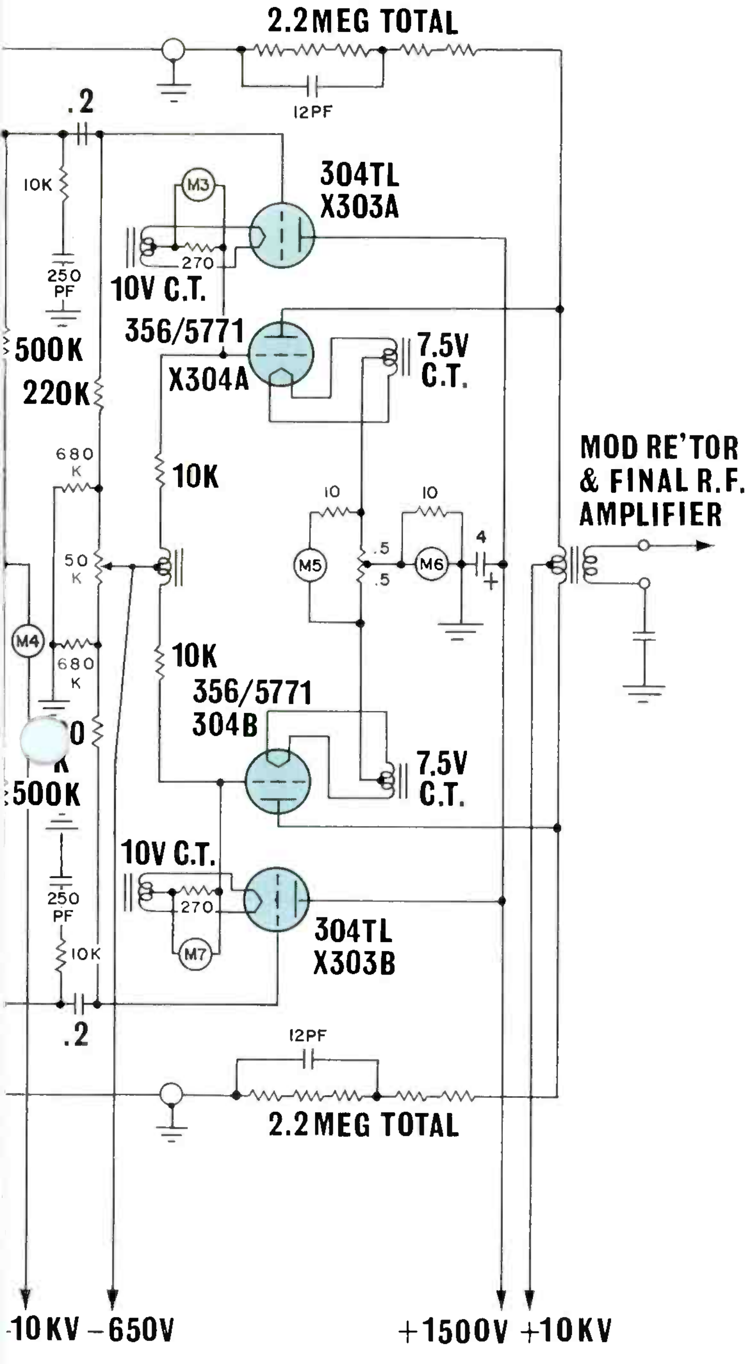


METER DATA

MI	0·5	MA
M2	100·0·100	MA
M3 M7	0·200	MA
M4	0·50	MA
M5	10·0·10	MA
M6	0·10	A

NOTES:
Unless otherwise specified, All Capacitances are Micro-Farads; All Resistances are Ohms.

Figure 3 — Schematic drawing of modified modulator section.



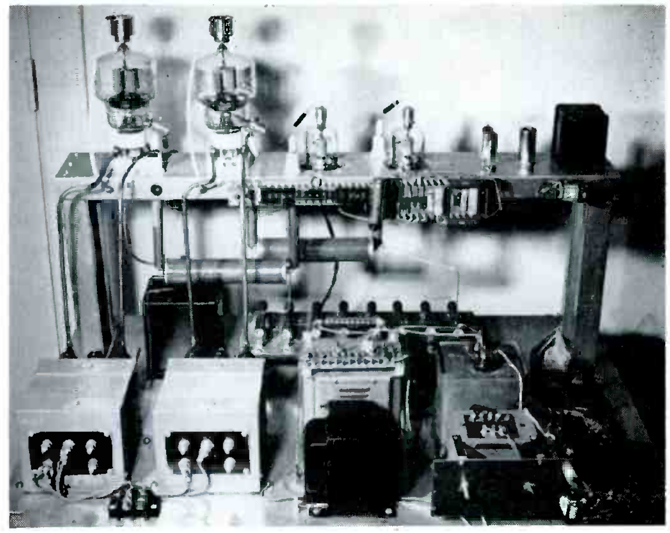


Figure 2 — Rear view of entire modulator driver. Transformers at left are 304 TL transformers with high voltage insulation for cathode follower service. The bias supply is in the center.

Based on greater life expectancy, lower tube costs and lower power consumption, it is estimated that $0.58 per hour saving is realized by both P.A. and modulator conversions. This figure is based on current advertised tube prices and a power cost figure of 1.5¢ per kWH.

Figure 3 is the final modulator schematic, and Figure 4 shows the performance curves at 50% (Figure 4a) and 95% modulation (Figure 4b) with transmitter input power of 65 kW and with 27 db of negative feedback.

Approximately 35 db feedback was obtained after many hours of trial and error testing. No trouble was experienced with low frequency instability, but several peculiar effects at frequencies from 20 kc/s to 150 kc/s were encountered, in addition to a troublesome VHF parasitic. When stability and a reasonable curve were achieved the feedback was backed off to 27 db with the resulting curves as shown. The resulting sound on the station monitor is very pleasing. Both lows and highs sound clean, and there is noticeable improvement over the old modulator.

Two features are worthy of note. In each stage there are "set" meters for setting the total plate current, and center-reading "balance" meters for balancing static plate currents of each stage. These meters also indicate dynamic balance. The balance control for the 12AU7 stage also balances the feedback. (The balance metering is not shown on the simplified schematic for the 4-65A stage.)

The second feature results from the direct-connected cathode follower circuit. The bias supply for the modulator tubes carries only the 304TL idle current, about 20 mA per tube. The grid current peaks are carried by the 304TL 1,500 volt supply. This resulted in replacing the old 3-phase heavy duty mercury-vapor bias supply with a much smaller single-phase supply using silicon rectifiers.

In order to minimize loss of air time, the entire driver unit was built on a 24″ by 35″ plate mounting a smaller deck on which the tubes were placed. This unit when completed and tested was placed temporarily behind the existing driver and temporary connections were made to use the new unit driving the 893's. The transmitter was actually operated about ten days like this with testing going on between broadcast schedules. The old driver was then removed, and the new slid into place with no loss of air time. Later the 893A's were replaced by ML-356's after all possible preliminary preparations were made. Five hours air time were lost here, but it was due to complications arising from inexperience in sweat-joint plumbing. About two hours air time were lost on other occasions due to troublesome things like VHF parasitics causing hot spots in neoprene water hose! (It was decided to replace the old porcelain water coils and connecting copper pipes with hose. High-priced hose with a neoprene core was tried, but this ruptured

TABLE I
OPERATING COST COMPARISON

Reduction in plate and filament power = 13.42 kW
(Reduction in filament power alone = 12.74 kW)
@ 1.5¢/KWH = $0.201/ hour saving

Tube costs per 10,000 hours:

Old	New
$6,668.00	$2,877.25
or $0.667/hour	or $0.288/hour

a saving of $0.379/hour

Total saving: $0.58/hour

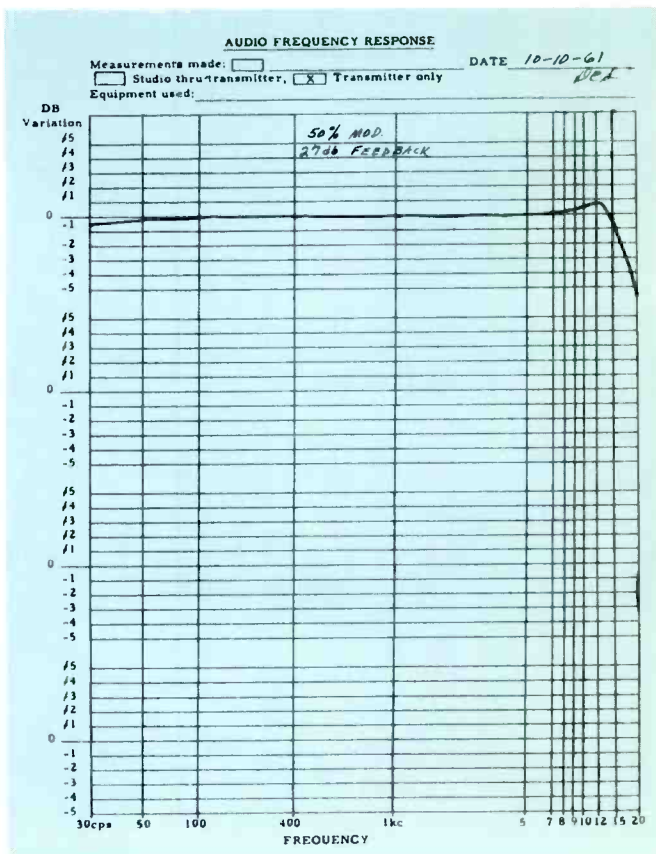


Figure 4a — Audio frequency response 50% modulation. 27 db feedback.

when a mysterious VHF parasitic which occurred under high percentage modulation caused hot spots. Three-quarter inch heavy-duty vinyl garden hose was obtained quickly and has proved very satisfactory.)

All bugs were finally eliminated bit by bit, and the modulator now performs very satisfactorily in every respect. In an effort to reduce construction costs as much as possible, surplus components were used where suitable. Also, thanks is due Eimac, San Carlos, California, for supplying engineering sample 304TL's.

Ideas for the basic circuitry were borrowed from an article, "Modulators For High Power Transmitters", by H. A. Teunissen, which appeared in the June, 1949 issue of *Communication News*, published by the Philips Telecommunication Industries, Hilversum, Holland.

Credit is due to Don Johnson, electrical engineer with Western Electric Company, Winston-Salem, N. C., for much of the basic design work and helpful consultation during testing; to Jim Barham of the KGEI staff for most of the construction and many hours of assistance during testing; to Bill Luck of Varian Associates, Palo Alto, California, for material assistance in various ways; and to K. G. Morrison, Western District Manager for Machlett Labs for the use of an HP-330B Distortion Analyzer.

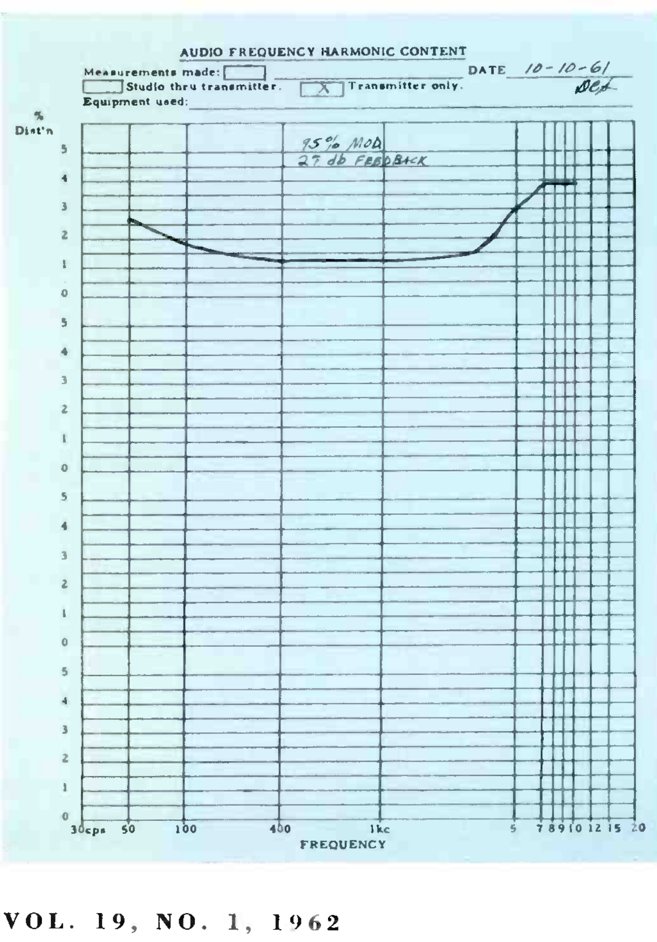


Figure 4b — Audio frequency harmonic content.
95% modulation.
27 db feedback.

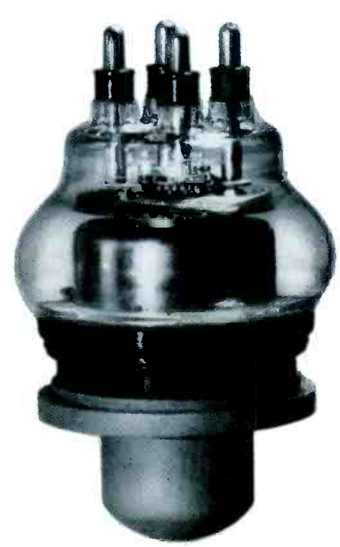
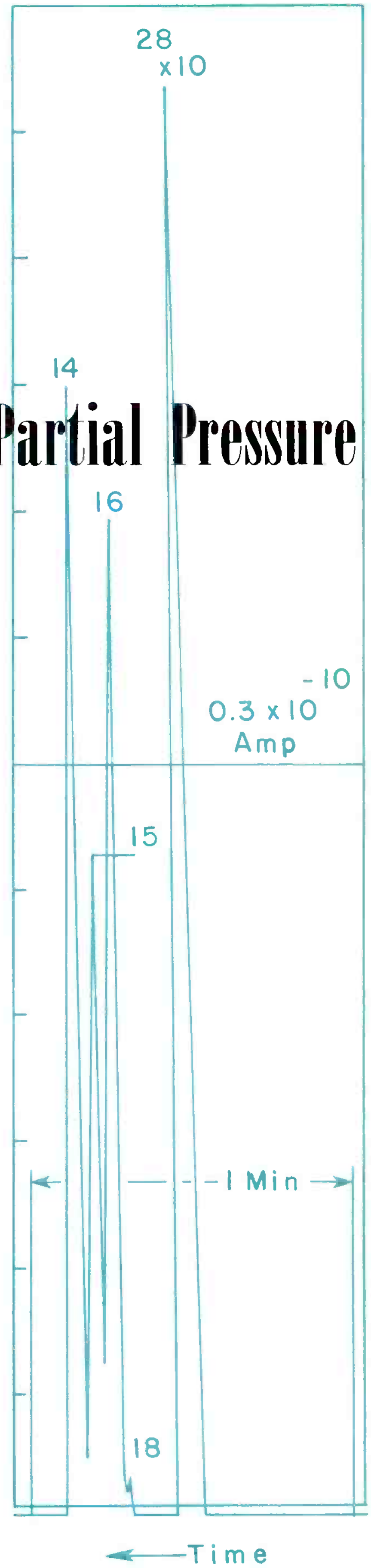


Figure 5 — ML-356

Partial Pressure



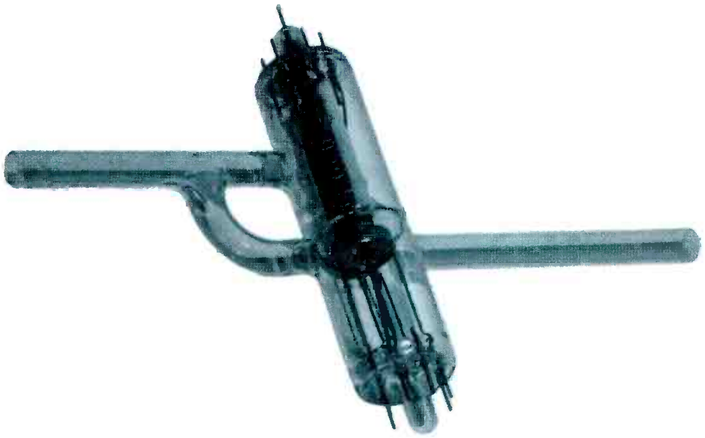
Ionization gauges are extensively used today for pressure measurements in a very wide pressure range (10^{-1} to 10^{-13} Torr). They are utilized in research as well as in production. The pressure measurement with all types of ionization gauges is based on a relation which exists between the measured ion current and the pressure in the system. This relation must be determined for each gas type by calibration. If a mixture of various gases or vapors is present in the vacuum system, the "total pressure" readings obtained by an ion gauge are approximate and can be expressed only in terms of "equivalent nitrogen pressure". It is well known that vacuum systems usually contain an unpredictable mixture of the different gases and vapors. "Total pressure" information given by an ion gauge is invaluable — which can be seen from the popularity of these gauges — but it does not reflect the true picture of the "vacuum".

In many applications, however, it became more and more recognized that the amount and nature of different compounds present in this "total pressure" must be known. The knowledge of the gas composition and the partial pressure of the components is of great help in solving various problems. The need for such partial pressure gauges can be shown in many examples: e.g., in a continuously pumped vacuum system a partial pressure gauge indicates readily whether the obtainable minimum pressure is limited by leaks, by the pump, or by improperly degassed parts. Other examples are: e.g., controlling the composition of all the residual gases in vacuum devices, ultra-high vacuum chambers in experimental work or in production, and measuring composition and purity of gases both in laboratory devices and in the upper atmosphere, etc. The demand for instruments to be used for partial pressure gauges for vacuum systems resulted in the development of a variety of such devices. The trend is to use partial pressure gauges in research and also in production where vacuum is utilized as an environment. Machlett Laboratories has selected two types of experimental partial pressure gauge tubes to introduce as production items.

The two selected partial pressure gauges are the rf type non-magnetic mass spectrometer tube and the omegatron tube.

They were selected because the rf mass spectrometer tube measures pressures in the high vacuum range from 10^{-3} Torr to 10^{-8} Torr, and the omegatron gauge supplements this by covering the ultra-high vacuum range from 10^{-5} Torr to 10^{-11} Torr. Their selection was based on the fact that both gauges have been tested and used in research in the last decade, and they have proved useful and reliable.

Gauge Tubes



by DR. PETER F. VARADI, The Machlett Laboratories, Inc.

I. RF Mass Spectrometer Tube ML-494 — Total and Partial Ion Gauge

The ML-494 non-magnetic type mass spectrometer tube with associated control circuits can be used for the simultaneous determination of total pressure of a gas mixture as well as determination of the partial pressure of the molecular species present. The sturdy and relatively simple gauge tube shown in Figure 1 was designed to operate in a wide pressure range as high as 10^{-3} Torr and down to 10^{-8} Torr. These features together with the fact that it operates without a magnet make this total and partial ion gauge suitable to replace the conventional ion gauges which are capable of measuring only total pressure. The importance of measuring gas composition in a vacuum system, beside monitoring the total pressure, is well established today, e.g., in the electron tube industry, vacuum evaporation and metallurgy, and in semi-conductor and thin film research.

The ML-494 is a radio frequency mass spectrometer tube (Figure 2). In this system gas molecules are ionized by an electron beam in the ion source of the tube. A part of the ions produced enters the analyzing chamber and is collected on the first grid (G 1). Similar to an ion gauge, the ion current measured here corresponds to the total pressure. Other parts of the ions produced travel through a grid system where ac and dc fields are used to identify ions having different masses.

Principle of Operation

The schematic drawing of the rf mass spectrometer (total and partial pressure) gauge tube is shown in Figure 2. The principle of the rf mass spectrometer is similar to that of the linear accelerator and utilizes only electric fields for mass separation.

Ion Source

The ion source of the tube is located in Chamber 1. It consists of ThO_2 coated tungsten spiral filament (F) as a cathode and a box-shaped anode assembly (A). The ThO_2 coating on the filament enables one to operate the cathode at a low temperature, and delivers 10 mA of electron current at 1300°C. The electrons emitted are accelerated towards the positive potential anode box (A). The gas atoms or molecules present are ionized in this box by the accelerated electrons. The ions formed here are then attracted towards the first negatively charged grid (G 1) into the analyzing chamber. Some of the ions flying into the analyzing chamber are trapped at this first grid, but others fly through this grid and travel through the analyzing grid system. It is interesting to mention that in this unique ion source for higher ionization efficiency, the direction of the electron and ion beams is the same. The complete elimination of the electrons from the ion beam produced is achieved by electric fields and a suitable tube geometry.

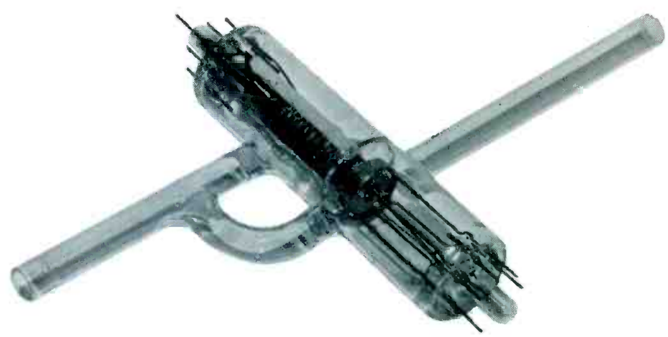


Figure 1 — RF Mass Spectrometer Tube.

Total Pressure Measurement

Ions collected at the first grid (G 1) are used for total pressure measurement. The filament cathode (F), the box anode (A), and the negative potential grid (G 1) can be considered as a conventional ion gauge. Ion current I^+ measured at this grid is proportional to the total pressure,

$$p = S\,I^+ \qquad (1)$$

Partial Pressure Measurements

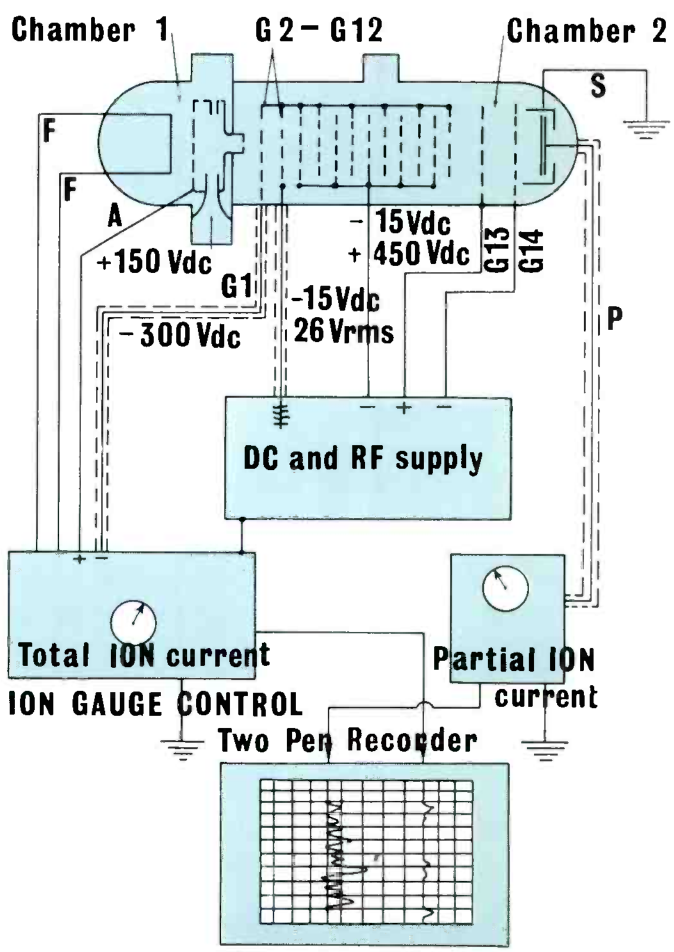
Ions not trapped at this grid (G 1) travel through the analyzing grid system. This part of the tube consists of 13 equally spaced grids. Grids G-2 through G-12 are all at the same negative dc potential, and between each alternate grid an rf voltage is superimposed. The rf voltage can be connected to each alternate grid only, the in-between grids being at rf ground, or a push-pull amplifier system may be employed. Ions traveling through this grid system gain energy from the rf field only if they have the proper velocity, v, to clear a grid distance, s, during a half period of the radio frequency, f:

$$\frac{s}{v} = \frac{1}{2f} = \frac{s}{\sqrt{\frac{2e_i}{m_i}\,Vo}} \qquad (2)$$

Here e_i and m_i denote the charge and mass respectively of the ions, and Vo is the ion accelerating voltage. Other ions not having the proper mass lose or do not gain energy while traveling through this grid system.

The wanted ions, having gained energy, and the ones not wanted are separated by the next to the last grid (G 13), on which a high positive "stopping" potential is applied. The positive potential of this grid is selected to repel all ions except those having gained the maximum energy from the rf field. The relation between the radio frequency, f,

Figure 2 — Schematic drawing of the RF Mass Spectrometer Tube and its Electrical Control System.



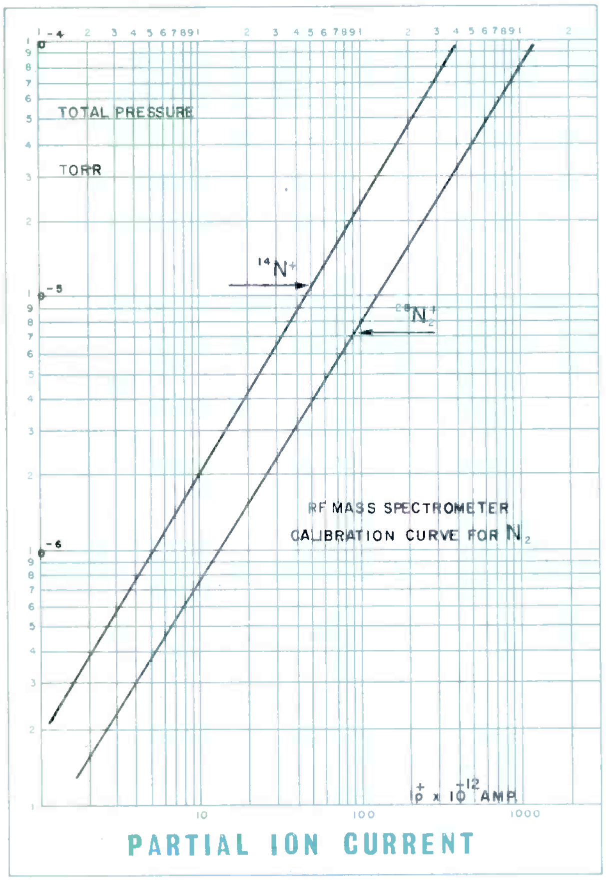
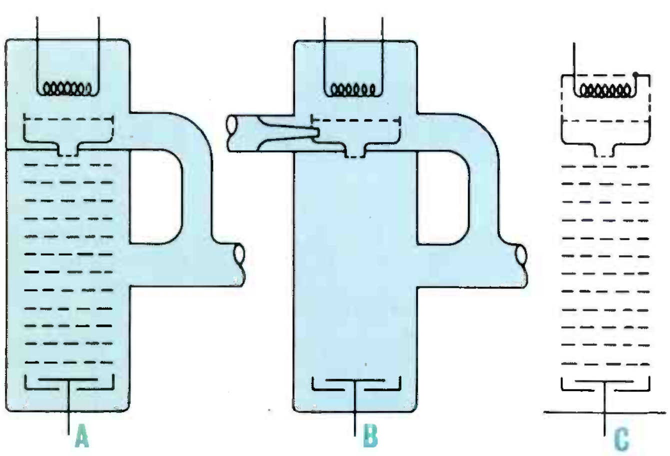


Figure 3 — Calibration Curve Plotted for Nitrogen.

Figure 4a — ML-494 Gauge Tube.

Figure 4b — ML-494A Throughput Gauge Tube.

Figure 4c — ML-494B Nude Gauge.



(Mc/sec.) at which a molecular species, M (atomic mass unit AMU), gains maximum energy can be derived from Equation 2 and written as:

$$M = \frac{K}{f^2} \qquad (3)$$

Here K denotes a constant, depending on voltages and tube geometry.

Only the ions wanted are able to pass the energy selector grid, G-13, and are collected on plate C. The resulting ion current is a measure of the abundance of this component in the gas mixture. G-14 and electrode S are for shielding the collector plate. Typical voltages used in this system are indicated also in Figure 2.

The importance of the high rf voltage has to be emphasized. High rf voltages (e.g., 25-40 V rms) are important to achieve high resolution and reliable operation of the system.

The partial pressure measurement in a system combines two tasks: (a) to identify the quality of the compounds, and (b) to determine their abundance. Quality identification is performed by scanning the mass spectrum and determining the components present. The scanning of the mass spectrum is performed by changing the radio frequency. To determine the mass number of the peaks in the mass spectrum, Equation 3 can be used. Having one reference mass, the equation can be written

$$M_x = M_o \left(\frac{f_o}{f_x} \right)^2 \qquad (4)$$

where M_o — AMU of the reference ion, M_x = AMU of the unknown ion, f_o and f_x are the frequencies respectively. The mass range in which this rf mass spectrometer tube can be used is M = 1 to M = 250 AMU. The accuracy of mass determination, based on Equation 4, is better than ±0.5%.

Partial Pressure Determination

Partial pressure determination of the gas components is based on a calibration similar to that described for the total pressure measurements:

$$p_x = C—I+M_x \qquad (5)$$

Here p_x is the partial pressure of the gas component. $I+M_x$ is the partial ion current of the component of mass M_x at a frequency of f_x, and C is a constant which has to be determined for each gas or vapor individually. The calibration curve for gases is linear up to 5 x 10^{-4} Torr, and measurements can be carried out as high as 10^{-3} Torr.

Calibration of the Total and Partial Pressure Gauge

The gauge has the feature that it measures total and partial pressures from the same ion beam. This makes its calibration extremely easy. The mass spectrometer system can be calibrated against its "built in" ion gauge. A calibration curve for nitrogen gas is shown in Figure 3.

Tube Design

The gauge tube can be made in three different forms, as is shown in Figure 4a, -b, -c. These are:

(a) As a regular gauge tube to be affixed to glass or metal systems (replacing ion gauges) ML-494.

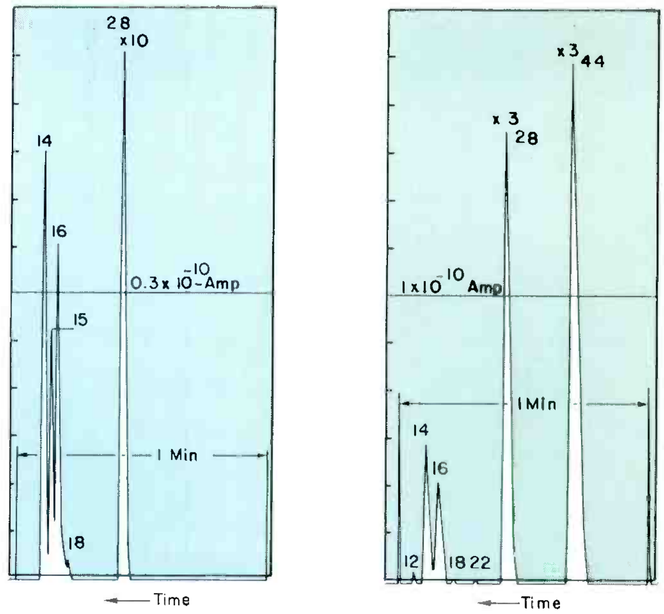
(b) As a through-put gauge, in which case the gases enter the ion source of the tube through a capillary thereby enabling measurement of the flow rate (ML-494A).

(c) As a nude gauge (ML-494B) which has no envelope and can be immersed in metal or glass systems.

The rugged and simple tube structure withstands shock (10 G in each direction) and vibration. Its features are: (a) the ion source can be degassed by electron bombardment; (b) it is bakable at temperatures up to 450°C; (c) the grids are mesh grids and are mounted under tension on a ring washer, resulting in a reproducible tube structure.

The performance and reliability of this mass spectrometer tube and system are based on our tube geometry and on the dc and rf voltages used. The equally spaced grid system and the high rf and dc voltages utilized make this mass spectrometer system a reliable gauge.

Mass spectra of gas mixtures containing N_2 and CH_4 and N_2 and CO_2 are shown in Figure 5, demonstrating the performance of the tube. Data were taken by a two-pen recorder and the voltages used were as indicated in Figure 2.



A Recording Chart of Spectrometer Output for N_2 and CH_4 Mixture (Total pressure 1.8×10^{-4} mm Hg nitrogen)

B Recording Chart of Spectrometer Output for N_2 and CO_2 Mixtures (Total pressure 1.3×10^{-4} mm Hg nitrogen)

Figure 5 — Mass Spectra of Gas Mixtures.

Scanning Speed

As can be seen from Figure 5, the scanning of the mass range M = 10 to 70 AMU was performed in these measurements in 60 seconds. The scanning speed of this total and partial pressure gauge can be varied, and also oscillographic recording may be utilized. The maximum scanning speed of this instrument is given by the electronics utilized. Fast scanning (sec./range) can be used if fast changes in the vacuum system must be recorded; while low speed (1 min.) can be used in most of the routine work. Slower scanning of the mass range can also be applied; however too slow scanning is not advantageous for the routine vacuum analysis. It is important to mention that the observation of a single component in the system is also possible by tuning the unit to the peak of the component. This is a feature if the changes in total pressure, and also the changes in the pressure of a single component, must be followed.

Electronics

The required control units are schematically shown in Figure 2. Typical electrical data of the tube are given below. The main units are the following.

Ion Gauge Control. Supplying filament current electron current stabilizer, positive anode and negative grid voltage and a dc amplifier for measuring the total ion current. The tube design is such that it enables the use of most of the commercial ionization gauge supplies available.

DC Voltages. May be obtained from batteries or any regulated power supplies.

RF Voltages. The frequency range and the required voltage is indicated in the specifications.

DC Amplifier. For the partial pressure measurement; must have sensitivity of 10^{-12} to 10^{-13} amp. if 10^{-8} mm Hg. partial pressures have to be measured.

The accuracy and sensitivity of the rf mass spectrometer tube depend on the stability of the voltages and on the sensitivity and response of the dc amplifiers used.

General Characteristics

Filament voltage, ac or dc	3 to 5	V
Filament current	2.5 to 3.5	A
Electron emission current (according to application)	0.1 to 10	mAdc
Electron current, maximum (for outgassing)	50	mAdc
RF voltage	25 to 50	Vrms
Frequency range	2 to 32	Mc/sec.
Corresponding to a mass range of	250 to 1	AMU
Resolution, manual scanning	60	
Resolution, ½ min. automatic scanning (10 to 65 AMU)	35	*
Pressure range, total and partial	10^{-3} to 10^{-8}	mm Hg.
Linear pressure range	5×10^{-4} to 10^{-8}	mm Hg.
Sensitivity (depending on the gas type) approximate value	10^{-5} A/mm Hg. for N_2^{28}	peak
Mounting position	Any	
Envelope	7052	Glass**

Figure 6 — Applications of the RF Mass Spectrometer Tube.

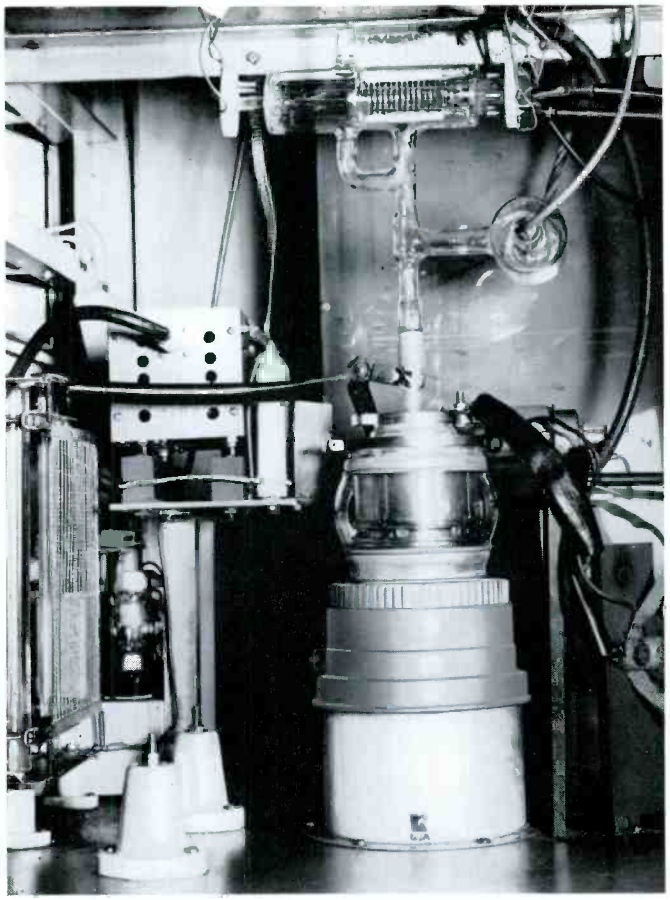


Figure 7 — Applications of the RF Mass Spectrometer Tube.

Applications

The ML-494 tube is equally suitable for scientific and industrial applications. This tube type was reported to be used successfully in a variety of such applications as:

a. *Gas analysis* during a pump process in conventional vacuum systems.

b. *Residual gas measurements* in sealed off vacuum devices (e.g., electron tubes).

c. *Studies on degassing* of materials, or gas permeation.

d. *Leak detection* in vacuum systems.

e. *Chemical gas analysis.*

f. *Space research.*

In the Machlett Laboratories these types of total and partial ion gauges have been used for years for controlling pump processes and improving the quality of power and x-ray tubes by measuring the residual gas composition in these tubes, Figures 6 and 7. This was possible because the ML-494 gauge tube does not require shielding, magnet, or any special adjustment. It can be used in power tube test sets without disturbing the operation of the tested tubes.

*Depending on the dc amplifier used.

**Graded or glass-to-metal seals available on request.

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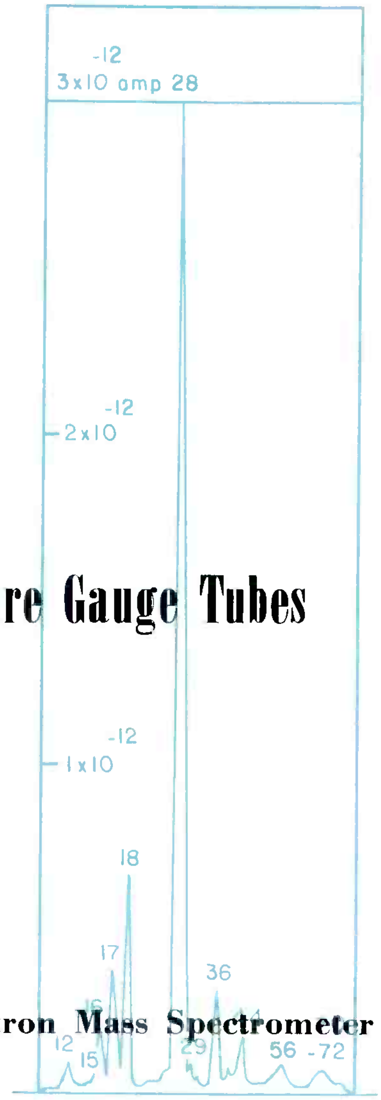
The above cited references are only a part of the more than ninety scientific papers published on the subject up to this time.

A complete listing of these papers may be obtained by writing to The Machlett Laboratories, Inc.



Partial Pressure Gauge Tubes

II. ML-573 Omegatron Mass Spectrometer High Vacuum and Ultra-High Vacuum Analyzer Tube

The ML-573 high vacuum (HV) and ultra-high vacuum (UHV) analyzer tube, generally called "omegatron", with associated control circuits, is a convenient, reliable tool for analyzing residual gases in vacuum systems in the pressure range of 10^{-5} to 10^{-11} mm Hg. The partial pressure gauge was developed primarily for ultra-high vacuum applications and was successfully used in solving a great number of analytical problems in vacuum technology in electron tubes, semi-conductors, and also in thin film research. Many types of ultra-high vacuum mass spectrometers were invented in the past decade, but among them the omegatron was chosen most frequently by leading scientists for their studies because of its many features. The main advantage of the omegatron is that, because of its extended use, its characteristics and operation are well established.

Operating Principle

The principle of operation of the omegatron is similar to that of the cyclotron. The omegatron tube Figure 8, is shown schematically in Figure 9. Gas molecules or atoms are ionized by an electron beam. The ions formed are subject to crossed magnetic and high frequency electric fields. Ions of a selected e/M ratio will move on a spiral path in the shielded volume until trapped by a suitably placed and shielded collector (C). The selection of an ion having a given e/M ratio may be accomplished by changing either the frequency of the applied electric field or the strength of the magnetic field. The relation between the mass number (M) of the selected ion, the rf frequency (f), and the magnetic field (B) can be given by the ion cyclotron frequency (f_c).

$$f_c = 1{,}525\ Bn/M \qquad (6)$$

where B is the magnetic field in kilogauss, f_c is the cyclotron frequency in Mc-sec^{-1}, n is the multiplicity of the electronic charge, and M is the mass number of the ions in atomic mass unit (AMU).

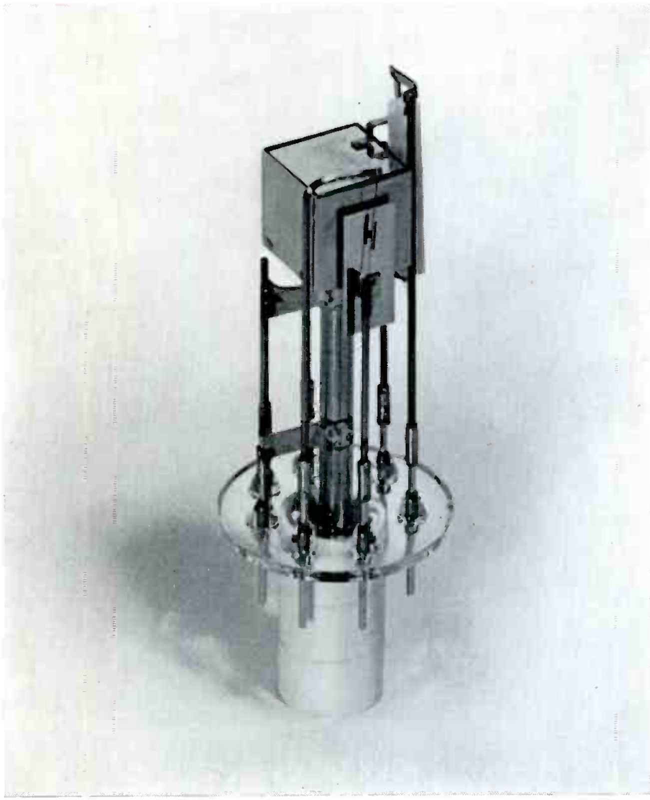


Figure 8 — Omegatron Tube.

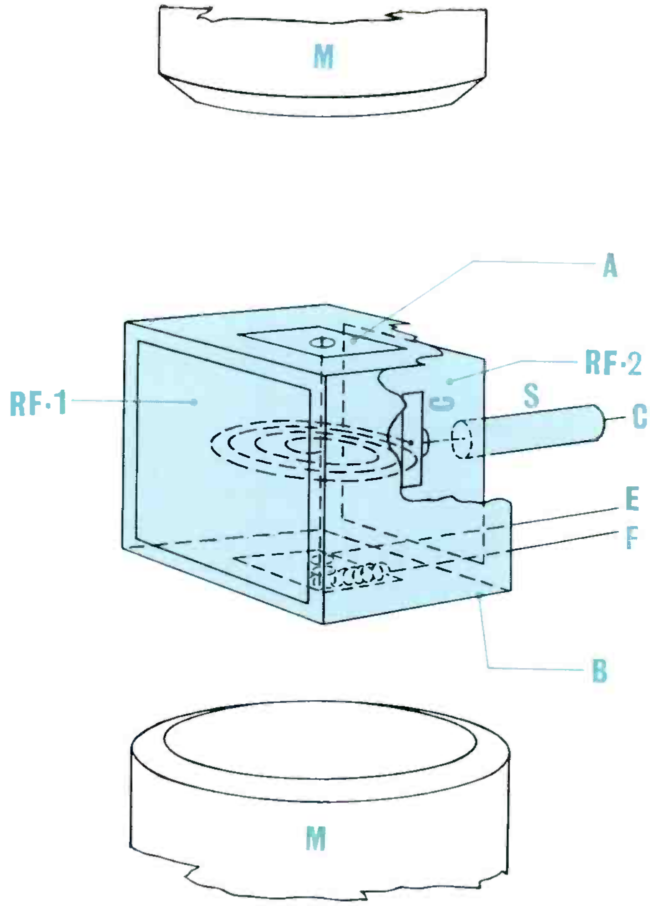


Figure 9 — Schematic Drawing of the Omegatron Tube.

Ions having the proper ne/M ratio for a particular rf applied frequency receive energy "kicks" with each revolution and travel in an expanding spiral and finally reach the collector. Other ions having unsuitable ne/M ratio, tending to lead or to lag in the rf field, lose energy after a small number of revolutions and remain close to the point of their origin near the electron beam.

The resolution of an omegatron can be given by the equation:

$$R = \frac{M}{\triangle M} = 96\, B^2 r_o / M E_o \qquad (7)$$

where r_o denotes the distance from electron beam to the collector in cm, and E_o is the amplitude of the electric field in volts per cm, and the other symbols are in the abovementioned units. An experimental value of the resolution may be obtained from scanning the mass spectrum.

The schematic drawing of the omegatron tube and its electrical supply units is shown in Figure 10. It consists of a spiral tungsten filament (F). The use of a spiral filament minimizes mechanical failures and makes the system more reliable and assures longer life. The tungsten filament at 5 volts ac operates at 1650°C. The cathode is usually at a negative potential with respect to the box-shaped structure (B), which structure can then, for convenience, be kept close to ground potential. Electrons emitted from the hot filament are accelerated toward the box and fly through the hole which is located in the side of the box opposite the filament. In order to avoid high and useless electron currents from the filament to the box, a cathode potential electrode is mounted between the filament and the accelerating box-shaped electrode. This electrode (E) has a hole in the center and focuses the electrons accelerated by the box into the hole in the box. The electron beam flying into the box can leave the box through a second hole opposite to the first, and reach the electron collector anode (A). This anode is

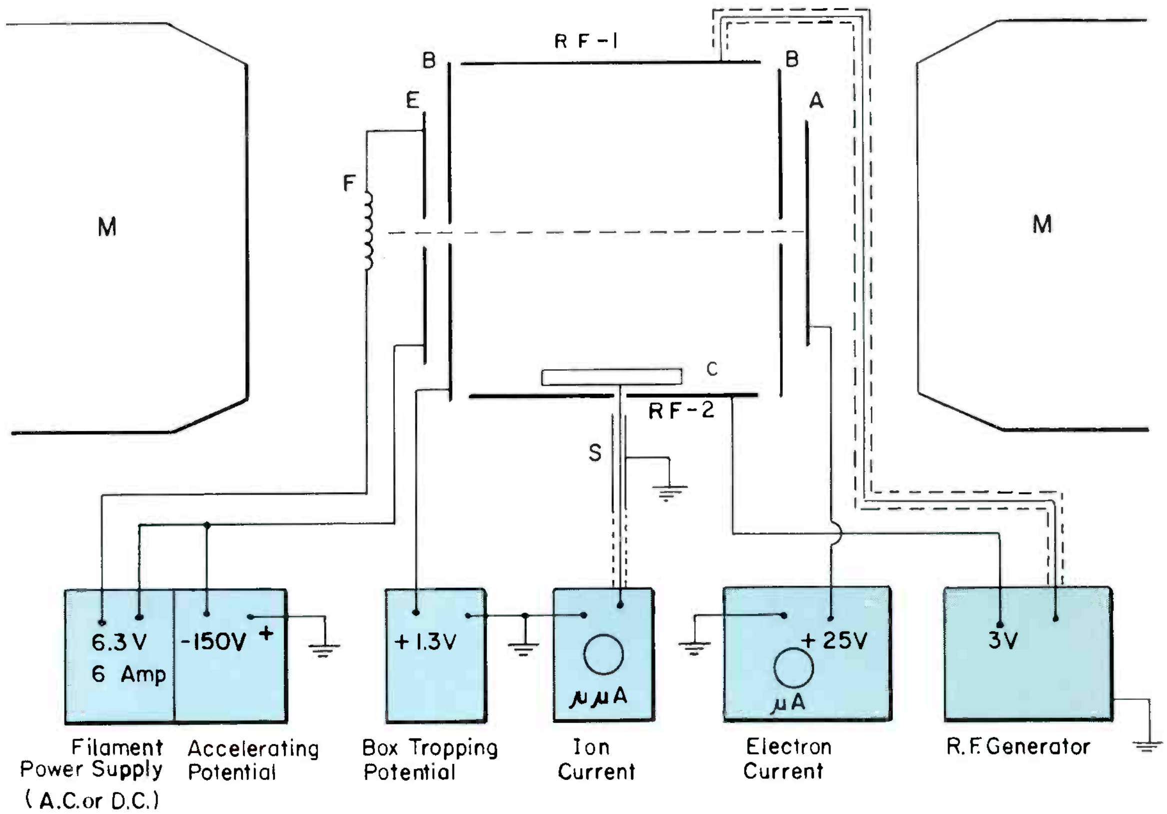


Figure 10 — Schematic drawing of the Omegatron Tube and its Electrical Control Units.

at a positive potential with respect to the box. The tube operation requires a homogeneous magnetic field. The direction of the magnetic field is parallel to the electron beam described above. The magnetic field can be produced either by a permanent or by an electromagnet as specified below, in order to get the electron beam through.

The top and bottom of the box are isolated rf electrodes. They are denoted in Figure 10 as RF-1 and RF-2 electrodes. Usually RF-1 electrode is connected to the rf voltage, while RF-2 is at ground or the two electrodes can be driven in push-pull. The selected ions produced by the electron beam are collected on a collector electrode (C), which is mounted inside the box, and has a shield (S) outside of the box.

The scanning of the mass spectrum is performed by changing the radio frequency. Mass spectra of residual gases are shown in Figure 11.

Design Features

The gauge tube is of a sturdy and relatively simple construction. It has a plug-in type socket and a small volume. The hard glass envelope permits bake-out at temperatures up to 450°C. The glass envelope fits perfectly in the magnet and minimizes the necessary adjustments. The tube structure is made of a special platinum-iridium alloy which can be degassed without causing changes in its shape or in the spacings and will not influence tube characteristics due to minor surface contaminations.

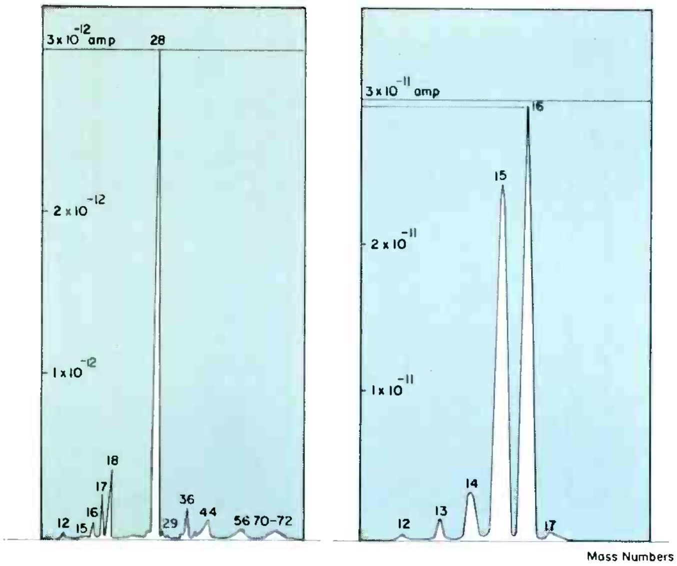
A picture of the ML-573 omegatron tube is shown in Figure 8.

Electronics

The control units required are shown schematically in Figure 10. Typical electrical data of the tube are given below. The main units are the following.

Filament Power Supply requires a unit delivering maximum 6.3 volts and 6 amperes ac or dc. The electron current can be selected according to the analytical application of the tube normally in the range of 1 to 15 μA. Because the electron current is limited by the filament temperature, the filament voltage must be either manually or electronically controlled to keep the electron current on a preselected value.

DC Voltage may be obtained from batteries or any regulated power supply. Three different dc voltages are required: the accelerating voltage, box trapping potential, and



MASS SCAN OF RESIDUAL GASES IN AN OIL DIFFUSION PUMP SYSTEM PRESSURE 6.5×10^{-7} mmHg FULL SCALE 3×10^{-12} amp

RESIDUAL GASES IN A SYSTEM CONTAINING CH_4 PRESSURE 5×10^{-7} mm Hg FULL SCALE 3×10^{-11} amp

Figure 11—Mass Spectrum of Residual Gases (Analyzed by Omegatron).

General Characteristics

Filament voltage, ac or dc	3 to 6.3 volts
Filament current	1.8 — 2.3 A
Electron emission current (according to application)	1 — 15* μA
RF voltage	0.5 — 3 Vrms
Frequency range	40 Kc — 6 Mc/sec.
Corresponding to a mass range of	100 — 1 AMU

*Higher electron current may be obtained, but proper care must be taken to avoid burning out of the filament.

Resolution	40†
Pressure range	5×10^{-5} to 10^{-10} mm Hg.
Linear pressure range	10^{-5} to 10^{-10} mm Hg.
Mounting position	Any
Envelope	7052 Glass**

Maximum and typical voltages are as follows:
(All voltages given with respect to ground)

	Maximum	Typical
Filament	—150 Vdc	—100 Vdc
Box (trapping)	+ 1.5 Vdc	+ 1.0 Vdc
Anode	+ 45 Vdc	+ 15 Vdc
RF 1	3 Vrms	2 Vrms
RF 2	3 Vrms	Grounded
Ion collector	Grounded	Grounded
Shield	Grounded	Grounded

A typical mass spectrum is shown in Figure 8.

†Resolution of the omegatron changes over the mass range. The resolution can be selected by the rf voltage applied. The theoretical resolution of this tube for M = 28 ions at 0.2, 1.0, and 2.0 Vrms are 200, 40, and 20 respectively (1).

**Graded or glass-to-metal seals available on request.

anode voltage. These voltages are preferably adjustable to suit the different applications of the omegatron tube.

RF Voltage. The frequency range and the required voltages are indicated in the specifications.

DC Amplifier. The dc amplifier must have a sensitivity of 1×10^{-14} A, for use in the UHV region.

The accuracy and sensitivity of the omegatron tube depend on the stability of the voltages and on the sensitivity and response of the dc amplifier used.

Magnet. The magnet should produce a uniform field of about 3400-4000 G over an area of about two inches in diameter, inside of a 1.5-inch air gap, for optimum resolution. A suitable magnet may be obtained from The Machlett Laboratories.

Adjusting the Magnet. The magnet has to be positioned so that the magnetic field aids the electron beam in travelling through the box. This can be achieved by positioning the magnet while the tube is in operation. The magnet is in position when we obtain maximum electron current on the anode (A) of the tube. The positioning of the magnet is easily achieved by a suitable adjusting table.

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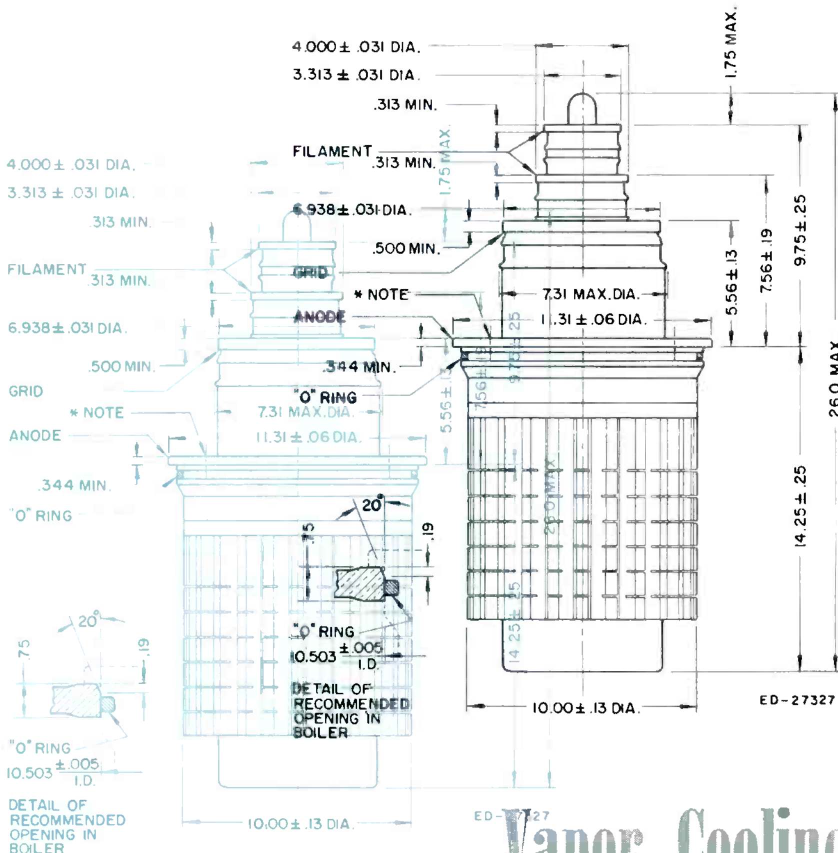


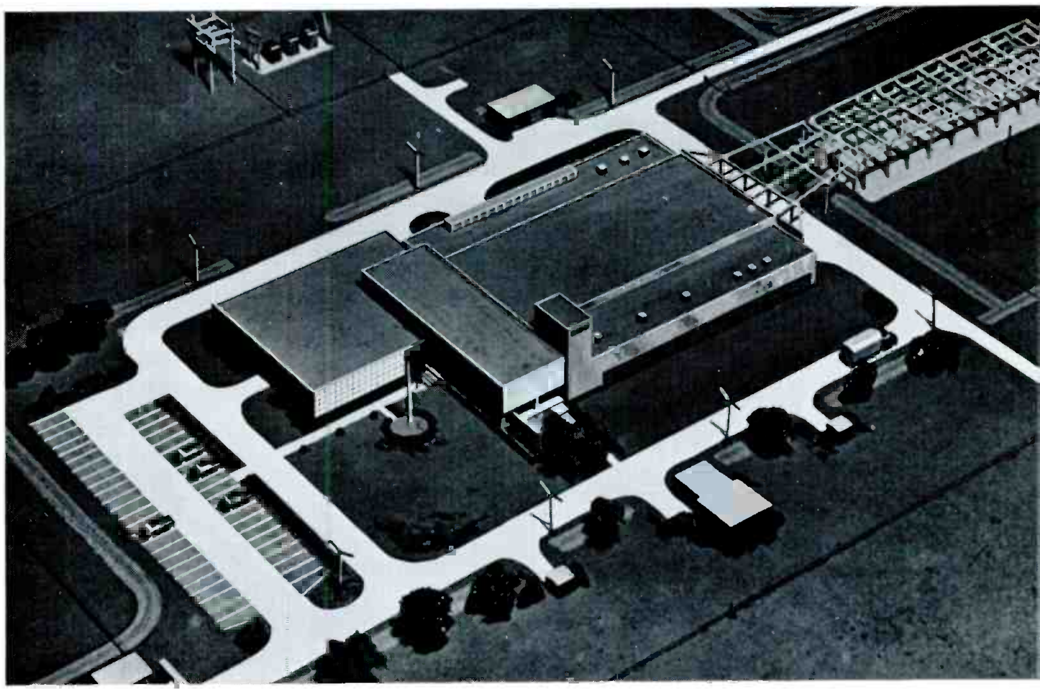
Vapor Cooling:

Its First Major American Installation in the

Introduction

On December 1, 1959, the United States Information Agency issued an invitation to Contractors to submit bids to the Agency for work on new facilities to be constructed in Greenville, N. C. The project was to be a major one; equipment would be used to broadcast Voice of America programs to the Voice's overseas installations for rebroadcast to the Communist countries. The General Electric Company was the successful bidder for the 250 kW transmitters called for by the Agency and The Machlett Laboratories is proud to have had its ML-7482 vapor-cooled triode chosen for use in these transmitters. Acceptance tests have been satisfactorily made and the new transmitters are scheduled for operation late this year.

Figure 1 — Model of one of the Voice of America transmitting stations being constructed at Greenville, North Carolina. The Voice of America is the radio service of the U. S. Information Agency. *(Photograph courtesy of U.S.I.A.)*



New 250 kW Voice of America Transmitter

Voice of America

The global radio network of the United States Information Agency is the Voice of America, the official radio of the United States. By direct transmission it speaks in 36 languages a total of 103 hours a day to an estimated audience of over twenty million people. (Through taped programs, used by local radio, the audience is nearly tripled.) Eighty-seven large transmitters now carry the "Voice" programs to Communist countries. Ranging in magnitude to one million watts carrier power, the transmitters of the U.S.I.A. use Machlett transmitting tubes in most of the key installations.

In operation since 1953, the megawatt transmitters have logged hundreds of thousands of air hours with the ML-5682 coaxial terminal triode. As it was the leading "communications band" triode of its time so now is the ML-7482, vapor-cooled coaxial terminal triode, employed in the six 250 kW transmitters of the Greenville facility (Figure 1). When completed this operation will consist of six 500 kilowatt, six 250 kilowatt and six 50 kilowatt transmitters. It will be the largest and most powerful broadcasting station complex in the world.

The basic technical purpose of Greenville will be to deliver a stronger signal to Europe, Africa, the Middle East and South America. It will provide a flexible relay system to overseas bases; direct short wave to specified areas; function, if necessary, as an emergency communications system and will replace outmoded installations elsewhere. Having a total

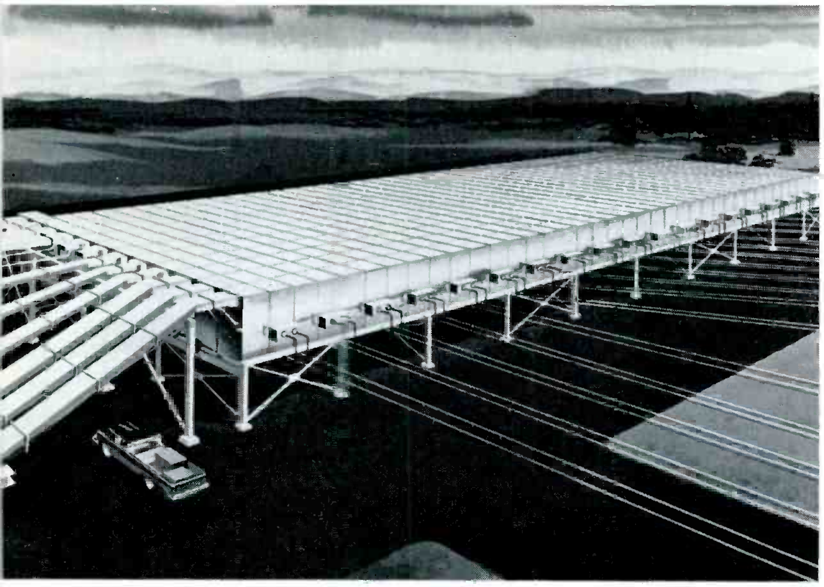
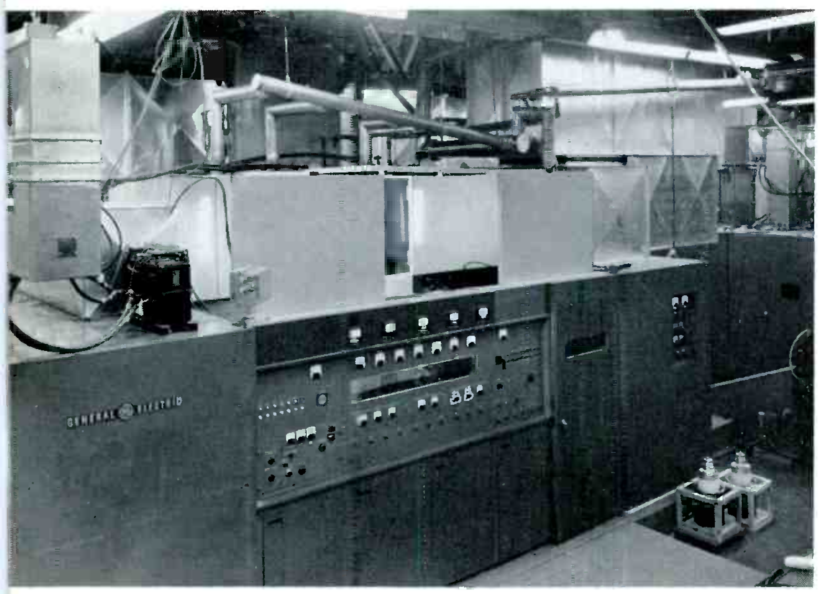


Figure 2 — Artist's conception of switchgear facility at Greenville, North Carolina, transmitter stations now under construction. Through this electronic mechanism, Voice of America programs from 22 transmitters can be beamed to East and West Europe, Africa, Latin America, and VOA relay stations around the world.

(Photo courtesy of U.S.I.A.)

Figure 3 — Front view of the new 250 kW AM transmitter manufactured for the Voice of America by the General Electric Company.

(Photo courtesy of General Electric Company)



installed capacity of 4820 kW carrier power the facility will transmit within the frequency ranges of 4 to 30 Mc. All transmitters, except for low powered units, will be amplitude modulated.

Two major transmitting sites, situated approximately 18 miles apart, have been established for the location of the various transmitters which will be equally divided in numbers and power between the two areas. Each installation is to be complete including all audio and program switching equipment, monitoring and frequency checking, transformer vaults, primary power distribution and so on.

A radio receiving unit will also be part of the facility, it too, will be located 18 miles from either transmitting site. This unit will serve for program, communications, miscellaneous reception and search as required.

Transmitting antennas are on a scale appropriate to the massive undertaking: one site employs 964 acres for the erection of thirty-seven h.f. transmitting antennas, the other 840 acres for erection of thirty-six antennas positioned with reference to a large number of bearings. The antennas themselves will be of the curtain and the rhombic type; the curtain antennas being used for the higher powers. The curtains at either site will be supported by 112 guyed steel towers ranging in height from 154 to 312 feet (Figure 2). Some rhombic antennas will also be used at the higher powers.

Complete antenna flexibility is provided. Any transmitter at the site will be capable of connection to any site antenna; all transmission line runs from each antenna farm will terminate at a transmission line switching bay located adjacent to the related transmitter building.

The New 250 kW Shortwave Transmitter

The General Electric 250 kW shortwave broadcast transmitter (Figure 3) is a high level modulated unit employing five ML-7482 tubes, two in the final position, two as modulators, and one driver. The transmitter is continuously tunable over a range from 3.9 to 26.5 Mc. Vapor-cooling, with forced-air-cooling for tube terminals and condenser unit, is employed for the high power electron tubes.

Transmitter Circuits

A block diagram of the high power stages of the transmitter is shown in Figure 4.

RF Final Stages

Two ML-7482 tubes are used in parallel in a grounded grid-circuit providing 250 kW transmitter output power. 25 kW of this power comes from the driver stage (also a grounded-grid configuration). Conservative tube operation is evidenced here by the fact that one tube alone could produce nearly the entire required output. Radio frequency output is pi-coupled to a harmonic filter consisting of five fixed-tuned filters.

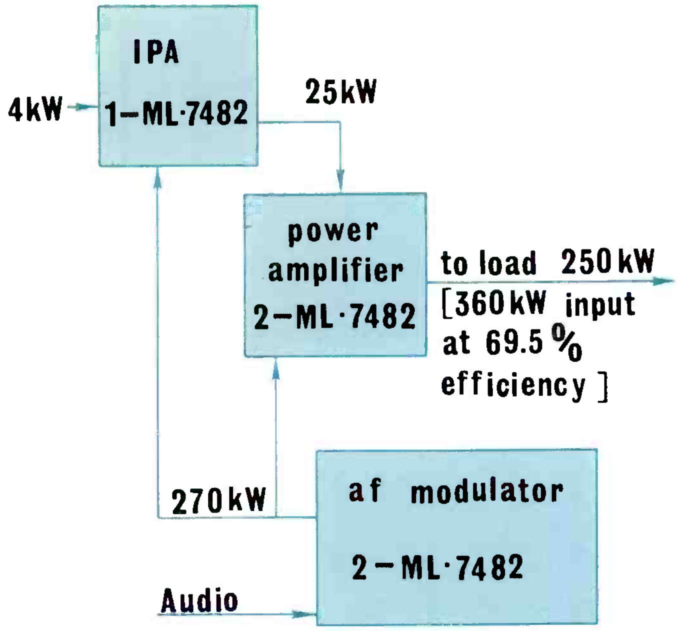


Figure 4 — Schematic diagram of the high power sections of the 250 kW transmitter.

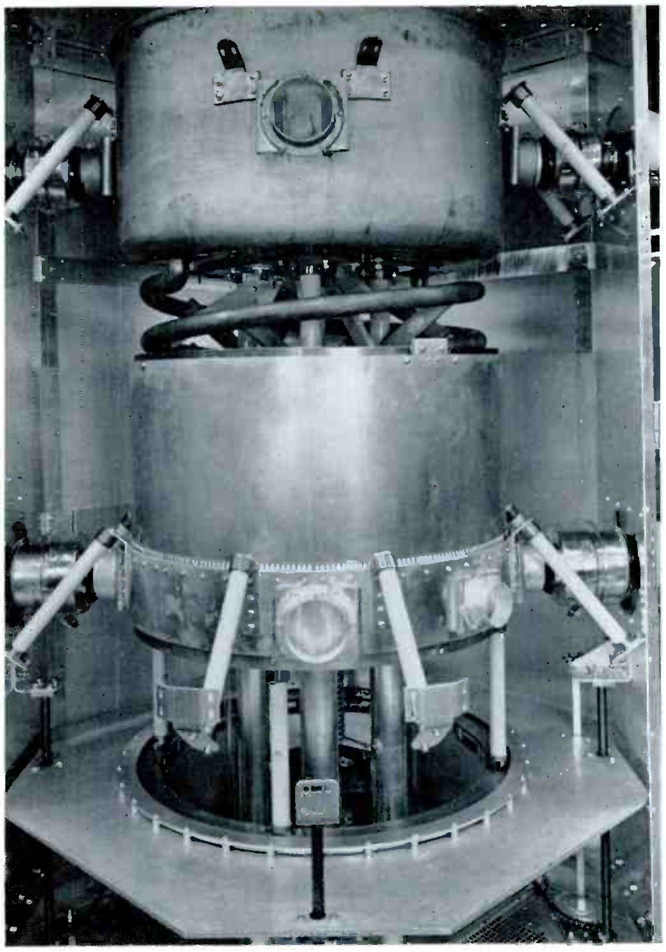


Figure 5 — Detail view of the final amplifier section. Two ML-7482 tubes each mounted in a "boiler", are both encased in a large drum. The drum forms part of the cavity-tuning system.

(Photo courtesy of General Electric Company)

By modulating both driver and final stages linearity is improved, grid heating of the output stage is reduced and negative modulation may be obtained without neutralization. By employing a grounded-grid cavity, circuit tuning stability under all conditions is achieved. The entire rf circuit configuration is clean and is easy to tune; only three variable components are found in each stage, these components being in the pi-coupled tank circuit.

The measured performance of the output and driver stages is as follows. This data represents the meter readings at the transmitter.

	Driver Tube	2 Output Tubes
DC Plate Voltage	12 kV	12 kV
DC Plate Current	3.5 A	26.5 A
DC Grid Current	1.0 A	7 A
Grid Resistor	300 Ohms	75 Ohms

The measured output into the load is 250 kW.
The input power to the two final stages is 360 kW.

The overall efficiency of the final rf amplifier chain including losses in the harmonic filter is 69.5%. This efficiency remains substantially constant throughout the frequency range.

Physical Construction Simplified — RF Amplifier Plate Circuit

The two ML-7482 final tubes, each mounted in a "boiler", are both encased in a large drum as shown by Figure 5. The drum, 32 inches in diameter, is the plate connection; 4 vacuum capacitors between the cavity walls and the drum are for plate tuning. The tank coil (a bi-filar helix of 2″ diameter copper tubing) carries incoming water to the boilers. The tank coil inductance continuously variable; two contacts, mounted on opposite sides of a large cylinder surrounding the coil, progressively short out the coil as the cylinder is rotated in a helix. The opposite terminal of the coil is formed by a 200 contact-finger band around the plate "cylinder"; four loading capacitors are connected to this band.

A clean plate circuit configuration is achieved by the cavity type grounded grid circuitry. As a result complete stability is achieved under all tuning conditions.

RF Amplifier — Cathode Current

The cathode circuit of the power amplifier is shown in Figure 6. The grids are rf grounded by a ring of ceramic capacitors. Two high current capability bi-filar chokes carry filament heating power. The pyrex glass insulating tubes seen in Figure 7 carry the steam from the boiler to the condensers.

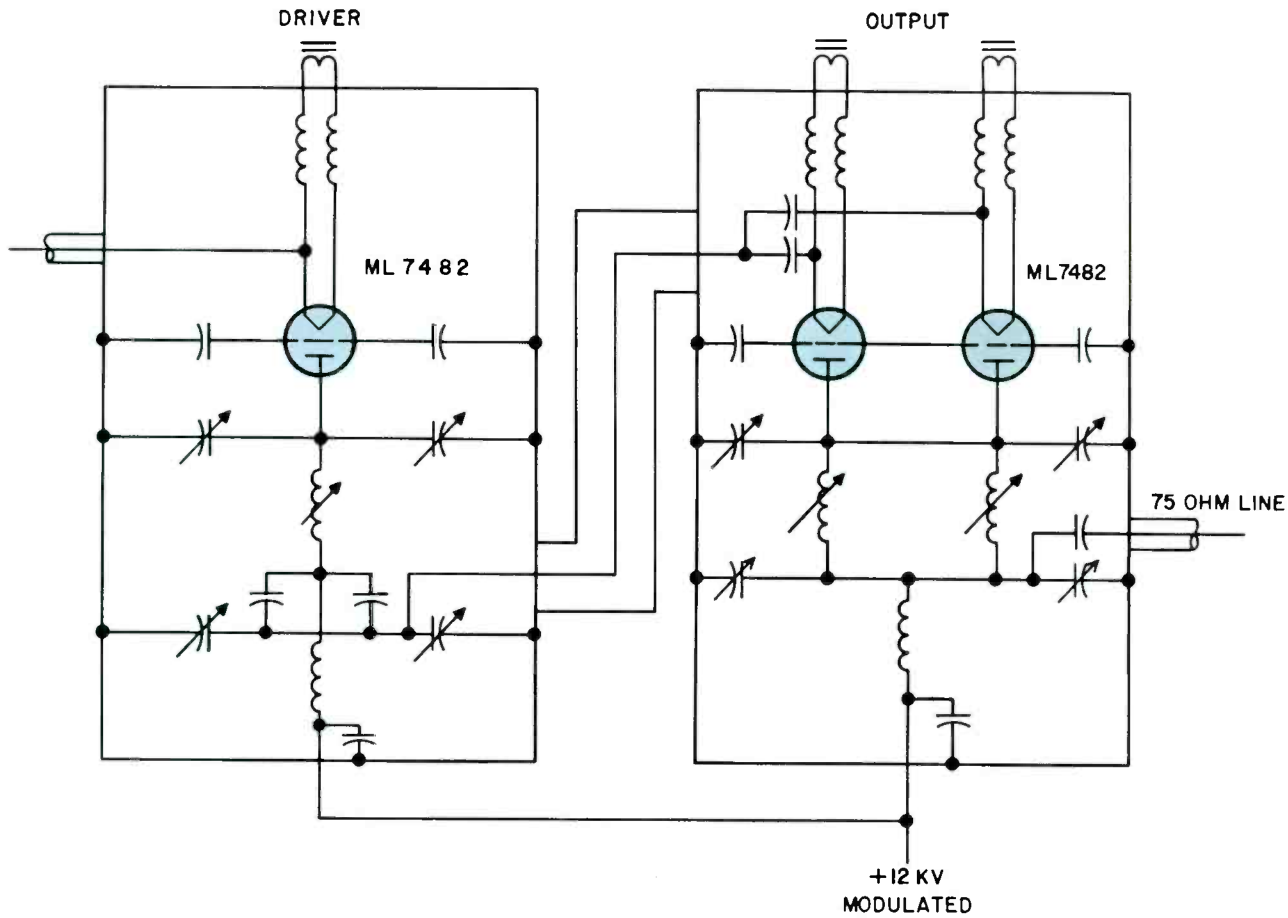


Figure 6 — Cathode circuit schematic of the final rf amplifier. Grounded grid circuitry is employed.

Simplicity of configuration also described the cathode circuit; no adjustments of any sort are required.

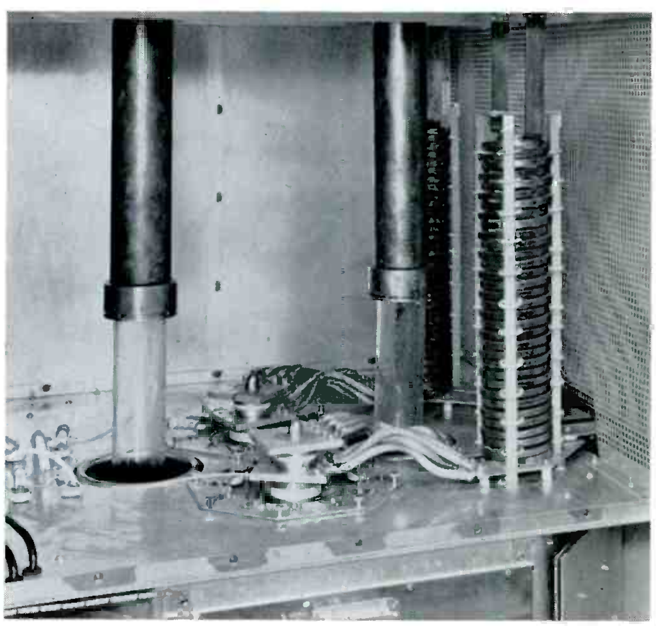
Modulator Circuitry

Design requirements for the transmitter specify heavy clipping of the program. The special VOA audio peak-clipping amplifiers are designed to improve intelligibility and to increase the average speech power without exceeding acceptable peak modulation percentages.

Because of this and the trapezoidal waveform needed to effect its accomplishment, the modulator power is 270 kW and not 180 kW, which would normally be required for 100% sinewave modulation of the 372 kW developed by the rf stage (372 kW at 67% gives 250 kW to the load.)

Additional audio requirements are also of a stringent nature; 100% sinewave modulation is required at frequencies from 50 to 10,000 cps and 100% trapezoidal modulation from 100 to 3000 cps with the trapezoid flat-top "tilt" less than 5%. This "tilt" requirement results in a need for an extended low-frequency response to a few cps. The fre-

Figure 7 — Upper section of rf amplifier showing cathode connections and Pyrex tubes which carry off steam created in anode "boiler". *(Photo courtesy of General Electric Company)*



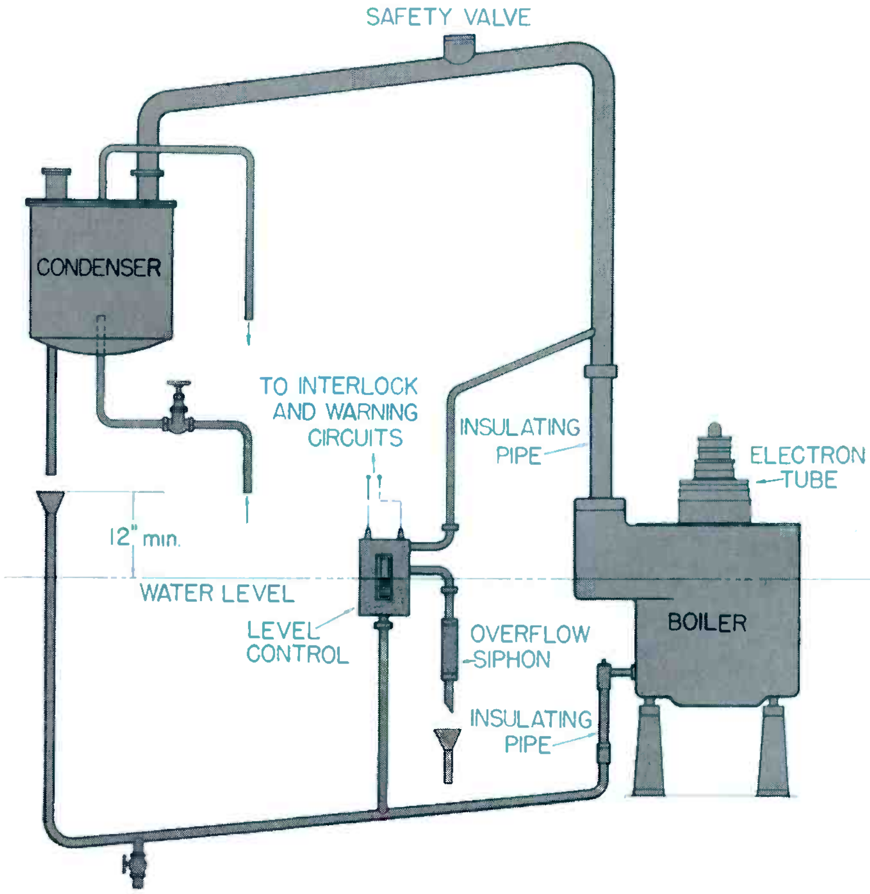


Figure 8 — Vapor Cooling, a schematic representation of the classic system.

quency response is to be flat to 3 cps.

An unusual 2-winding modulation transformer, center-tap grounded, is employed to provide maximum audio bandwidth. By omitting the conventional 3rd transformer winding a high inductance is achieved together with a small leakage inductance. The grounded center-tap circuitry aids low frequency response by eliminating the modulator plate supply filter from the path of the audio power from the modulator to the rf amplifier.

A low frequency boost prior to the modulator tubes was employed to compensate for the modulation transformer and coupling condenser droop, and therefore to achieve a flat response below ten cps. This compensation results in the requirement for an increased modulator tube plate voltage swing at low frequencies bringing the modulator stage dc plate voltage requirements to 15 kV.

The modulator performance data is tabulated below:

	100% Sine	100% Trapezoidal
DC Plate Voltage	16 kV	16 kV
DC Current (per tube)	9.5 A	12.5 A
DC Grid Current (per tube)	0.5 A	2 A
Circuit Efficiency	59.2 %	67.5 %

Vapor Cooling — Basic Principles

In conventional water-cooled power tube systems, the thermal energy of the anode is transferred to the circulating coolant, which subsequently exhibits an increase in temperature. With vapor cooling, however, a fundamental departure in principle is involved: thermal energy is absorbed by a change in the physical state of the coolant, rather than an increase in its temperature. The key to the efficiency of this system lies in the ability of vaporizing water to absorb huge quantities of heat. In a typical water-cooled installation, the coolant experiences a 20°C rise in temperature; thus, each gram of the water absorbs 20 calories of heat. In a typical vapor-cooled installation, water at 95°C is converted to steam at 100°C and 545 calories per gram of coolant are absorbed. The greater thermal capacity of the coolant under these conditions will support anodic dissipation 10-20% higher than other systems, and offers enhanced protection against thermal overloads.

In operation, the rugged copper anode of the vapor cooled tube is immersed in the distilled water within the boiler. The heat generated within the anode is absorbed by vaporization of the water. The diagram of Figure 8 illustrates the classic system.

As the water experiences a 2000-fold increase in volume during vaporization, a powerful turbulence is created within the coolant. The heavy ribbed anode fins of the vapor cooled tube are designed to take advantage of the turbulence to achieve a vigorous "cleansing" action, precluding the formation of an insulating vapor film on the anode which could lead to excessive local heating.

Steam generated in the boiler is conducted to an air-cooled heat exchanger and the resulting condensate is returned to the boiler. No water pump or external source of energy is normally necessary to circulate the coolant. A density gradient of the coolant within the boiler is established in the process of absorbing anode heat, resulting in a thermo-syphon effect sufficient to insure proper coolant circulation over the whole range of possible operating conditions.

Proper coolant level within the boiler is usually maintained by a feed tank arrangement that capitalizes upon the natural tendency of water to seek its own level. Continued function of this inherent regulatory mechanism is provided by the closed cycle nature of the design which insures that the quantity of coolant in the system remains constant.

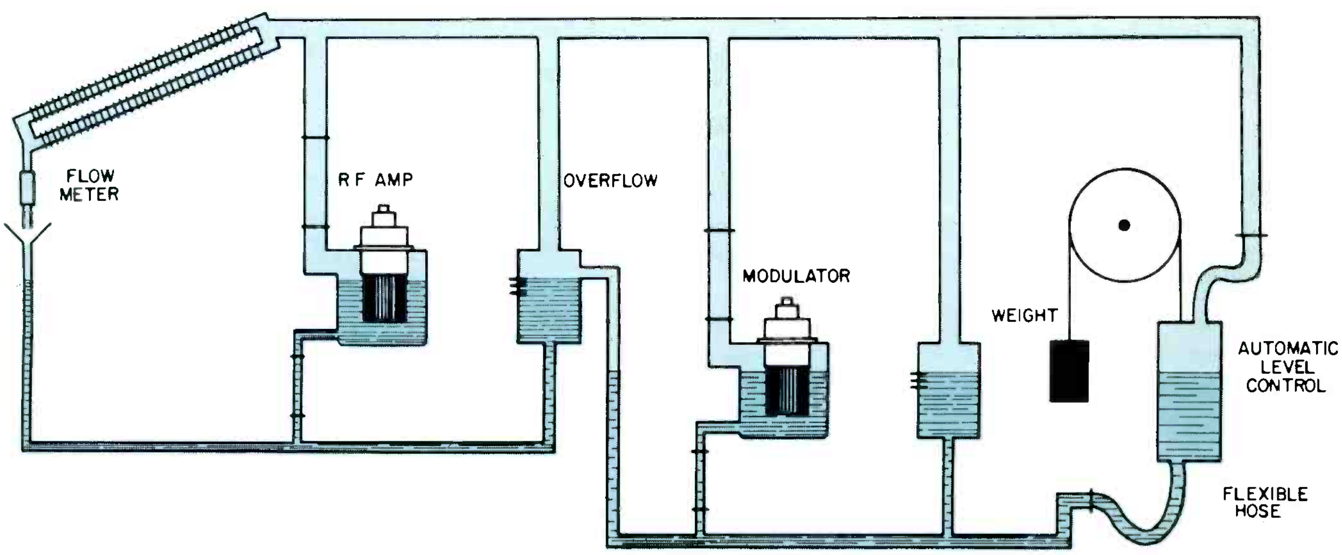
The boiler, at anode potential, is electrically isolated from the rest of the cooling system by short lengths of insulated tubing. The use of short, mechanically stable insulators is permitted by the low flow rate requirement (about .09 cu. ft./min. for 100 kW), and the excellent dielectric properties of steam.

Vapor Cooling System — 250 kW Transmitter

The vapor cooling system of the 250 kW transmitter operates at a pressure of 6″ of H_2O; tube weight alone (130 pounds) maintains the tube in proper position in the boiler, the system being sealed by an "O" ring gasket located on the tube just below the upper flange on the anode.

Figure 9 — Vapor Cooling system employed by the 250 kW Voice of America transmitter.

(Photo courtesy of General Electric Company)



Since, for electrical and physical reasons, the rf amplifier tubes and boilers are located above the level of the modulators, and since a common cooling system was desirable, two water levels are required in the 250 kW transmitter, as shown by the schematic diagram, Figure 9. Salient features of the system are as follows:

1) A common condenser is used for the entire transmitter. This arrangement is more efficient than use of separate condensers. This is because the rf and modulator tubes exhibit maximum anode dissipation at 100% and 60% modulation, respectively.

2) RF tubes are connected according to the classical system; excess water from condensers returns to the modulator system.

3) Modulator system provides for an automatic water replenishment to accommodate delay in production of steam and return of water.
Automatic level control is provided by counterweighted tank (See Figure 10). Should the boiler level drop, the level of water in the tank drops making the tank lighter and permitting it to be lifted and therefore to restore water to the boiler via a flexible hose.

4) Condensers are forced-air-cooled using same blower system employed to cool tube terminals and transmitter cabinets.

5) System Capacities:

Water	26 gallons
Power Dissipated at 100% Modulation	320 kW
Water Flow at 100% Modulation	2¼ gpm
Steam Pressure	1 p.s.i.
Total Area of Heat Exchanger Tubes	112 sq./ft. (4 rows each 28 sq. ft.)
Air Flow through Heat Exchangers	20,000 cfm
Air Temp. Rise	55°F.

ML-7482

Of conservative and proven design, the ML-7482 triode, Figure 11 (and its water-cooled counterpart, the ML-7560) provides a coaxial terminal construction (such as introduced

Figure 10 — The ML-7482 employs ceramic insulation and uses coaxial terminal construction.

Figure 11 — ML-7482: Massive components of the anode assembly achieve a rugged efficient structure.

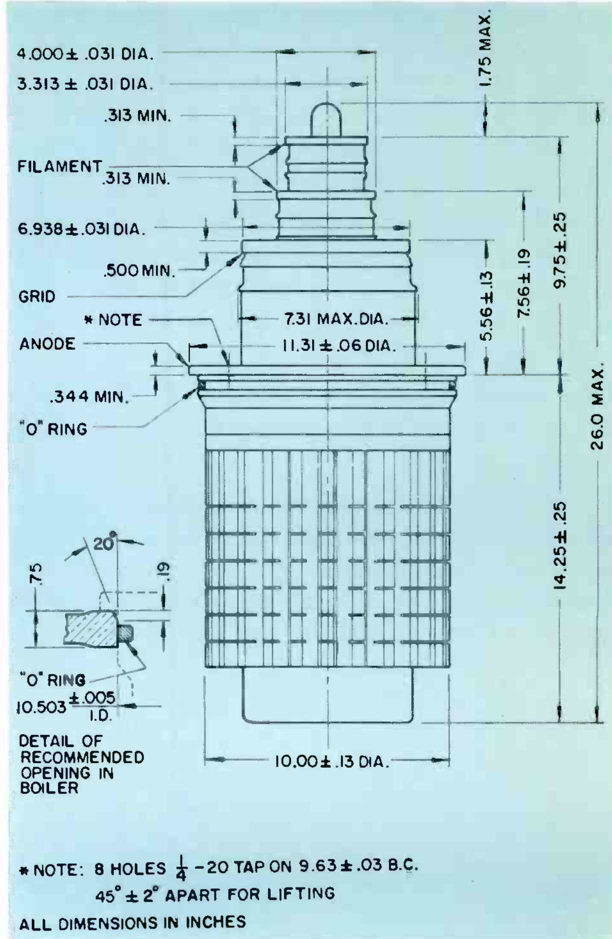


Figure 12 — ML-7482 Outline Dimensions.

by the ML-5681) together with high alumina ceramic cylinders for insulation. Manufactured with a technique proven by the ML-7007 (a highly popular VHF television tetrode) the ML-7482 terminal section is fabricated in a "hydrogen furnace". The reducing atmosphere of the furnace ensures parts cleanliness and obviates the need for subsequent cleaning.

In addition to its advantages in fabrication, the high-alumina ceramic permits high outgassing temperatures, exhibits a lower rf loss factor than glass, and demonstrates a low gas level as indicated by excellent stability under high voltage. The cleanliness of the tube interior is conducive to longer cathode life — a fact amply demonstrated by the comparative life figures of the ceramic envelope ML-7007 and the glass tube it has replaced: tube life has been increased on the average by a factor of two to three times.

The anode of the ML-7482 is made from heavy wall copper tubing. It is fabricated by brazing a bottom plate, heavy notched ribs, top flange and kovar final seal to the tube (Figure 12).

Electrical characteristics and maximum ratings for the ML-7482 are given in Table I.

TABLE I

Electrical Characteristics:	
Filament Voltage	16.5 volts
Filament Current	450 amperes
Amplification Factor	45
Maximum Ratings — RF Amplifier — Oscillator (Class C Telegraphy)	
DC Plate Voltage	20,000 volts
DC Grid Voltage	—1,500 volts
DC Plate Current	30 amps
DC Grid Current	4.0 amps
Plate Input	600 kW
Plate Dissipation	200 kW

• • •

The Machlett Laboratories' continuing participation in programs of national interest and importance — such as the Voice of America Greenville project — is a source of great satisfaction to the Company and provides also, a demonstration of the quality and reliability of its products.

The ML-8087, a New Tube for Scan Conversion

by SAMUEL T. YANAGISAWA, Manager Photosensitive and Storage Display Tube Division

Introduction

Several years ago, electrical-signal storage tubes were developed that made possible a large variety of signal and information processing techniques. These tubes were called "scan converter tubes" when constructed with two electron guns that could simultaneously write and read stored information independently of each other. As with most first production models, these tubes had their limitations and in time, the performance requirements of new applications became increasingly varied and more demanding. The Machlett Laboratories, together with the Compagnie Generale de Telegraphie Sans Fil of France, anticipated many of these requirements and developed a new tube. The ML-8087 has features not available heretofore with the result that both equipment manufacturers and users can now enjoy a simplicity of design and usage with high performance capabilities.

Applications

The use of scan converter tubes has spread so rapidly into many fields that it is of interest to review some of the present applications.

The first in point of time and the largest use at present is in radar bright display equipment for the surveillance and control of aircraft while en route between airports and during the approach and departure phases of traffic control. PPI radar information is fed directly into a scan converter and is converted to be displayed as a bright, flicker-free television type of display on several consoles. Fully controllable storage of this information enables the observer to see the aircraft as bright dots with fading trails that, in themselves, indicate the heading, the paths followed, and also the relative speed by the length of the trail and by the distance between successive past positions. This technique eliminates the need for remembering and tracking successive radar returns as was formerly necessary. It also immediately differentiates between moving aircraft and stationary clutter. The ease of observation greatly relieves the viewing tension and increases observer efficiency. The storage of these returns also aids in the display of airborne beacon returns for identification and control. The same advantages of scan conversion and storage are used in other radar applications wherever detection efficiency and operator fatigue are concerned.

Scan conversion tubes are being used to transform from one set of television standards to another, such as in the case of European or British programs that are to be rebroadcast in the United States or vice versa. Video tape can now be scan converted to be reused on any local standards. The problems of network synchronization can also be eliminated by rebroadcasting at the local line and frame rates.

Band compression to reduce video or informational bandwidth can be accomplished a number of ways; i.e., readout by a slow spiral scan, by slow television raster scan, or by a reduced sampling scan. Conversely, low frame rate information can be converted into a flicker-free rapidly scanned visual display.

An interesting application in astronomical observation is the improvement of signal to noise ratios by ability to integrate video signals over a number of scans to enhance the contrast over the existing noise level.

With the scan converter, analogue information on a given time base can be changed to a variable time base with or without a controllable delay. This finds application in some types of signal simulation equipment.

Sonar displays are improved with the storage capabilities and flexibility of operation being important factors.

In more complex equipment, three scan converters can be used, each to store a separate color. Readout into a color television tube produces a display with fading storage in which color signifies a fourth parameter such as altitude or identification of stored information.

Three dimensional radar displays are proposed showing the illusion of height so that aircraft trails may be observed in the vertical dimension.

Another application that has been discussed recently is the correlation of statistical data through signal processing and storage in scan converter tubes.

The applications of signal and information processing with these tubes are still increasing as circuit and equipment designers continue to explore the possibilities.

Features of the ML-8087

Intensive and continued development of the storage target and both the writing and reading electron guns have culminated in this new tube which has no crosstalk, high resolution, a fast and complete erase cycle, and a wide storage range.

Until the development of the ML-8087, scan converter tube types had "crosstalk". This was undesired feedthrough of the written signal directly into the reading circuit where it was displayed as unsynchronized background noise. Various methods to circumvent this crosstalk have had to be used, such as rf modulation of the reading beam or video cancellation circuits. Rf carrier techniques entail a loss of signal power during the process of detection in the reading circuit and thus lower the signal to noise ratio. Extensive rf shielding is necessary to avoid undesirable parasitic effects, in addition to the required rf circuit. Video cancellation techniques are simpler but require additional internal tube shielding to avoid undesired effects during intentional write sweep overscanning or offcentering. Now, with the precision ML-8087, the circuit and equipment design is simple and straightforward since no crosstalk exists.

Both writing and reading guns have been designed to give wide dynamic range and high resolution. The tube when used in PPI to television scan conversion will resolve a minimum of 170 range rings at 50% modulation and an ultimate resolution of over 200 range rings when used with a 945 line raster on the read scan. The resolution when used in orthogonal television raster conversion is up to 1000 TV lines. To obtain the full benefit of the resolution capability of this tube, electrostatic dynamic focussing of the read electron beam must be provided and the bandwidth of the video circuits must be sufficient to pass all the information.

The stored information can be erased in a maximum cycle time of 2 seconds at the long storage setting. In the usual case, the erase time can be much less. The reading process in this, as in all bombardment induced conductivity tubes, also acts to slowly erase the stored information. Normally, the greater the beam current, the shorter the storage. The wide storage range is obtained by varying the collector voltage and the beam current, usually between 0.5 to 5.0 microamperes. During the erase cycle, the beam current is increased by an erase electrode to over 100 microamperes. This greatly increased beam and an erase cycle procedure to the storage target backing plate quickly erase all the stored information down to the noise level. Information can be written and read at full amplitude immediately after the erase cycle is completed without the use of any special writing intensification circuits.

The wide storage capability of the ML-8087 enables it to read information continuously for minutes or it can read and erase information in one television frame scan. This latter short storage ability allows the tube to scan convert between television standards perfectly with no lag or drag of one picture frame into another which would tend to blur fast motions. No other scan converter tube can do this particular task as well.

The principle of bombardment - induced - conductivity makes possible very fast writing rates and allows the use of very short time base sweeps. In addition the response from large and small areas are of uniform amplitude so that intensities corresponding to the original written information are preserved. The level for the Minimum Detectable Signal does not change at a given setting.

The dynamic range is such that noise or "grass" may be written and read without being swamped by the highlights.

There are no collimation problems as both writing and reading beams strike the target at high velocity and are not decelerated. This also results in high linearity of transformation, no pattern distortion, high accuracy of registration, and eliminates any drift stability problems.

Conclusion

The Machlett Laboratories has developed the ML-8087 as a precision scan conversion tube. Its application is simple and reliable. Its adjustments are few and it can be changed in the equipment in less than five minutes.

In a succeeding issue of CATHODE PRESS a detailed technical article about the ML-8087 and its application data will appear. In the meantime, the Engineering Department will be most happy to answer any inquiries.

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*The impact of high speed writing electrons, in this instance, causes conduction within the dielectric storage medium in accordance with the stored pattern created by the electron bombardment.

DVST

Announcing Machlett

Direct View Storage Tubes

ML-8130
ML-8139

Brightness: Over 2000 foot lamberts — ML-8130
Over 1500 foot lamberts — ML-8139

Writing Speed — at full brightness:
Over one half million inches per second — ML-8130
Over 150,000 inches per second — ML 8139

Storage: Uniform Storage Characteristics

Resolution: To 80 written lines per inch at optimum brightness

Focus: — both tubes: Electrostatic

Deflection: ML-8130 — Electrostatic
ML-8139 — Magnetic

The Machlett Laboratories, Inc. announces the availability of two new Direct View Storage Tubes, ML-8130 and ML-8139. (Available also in non-shielded versions as ML-7222 and ML-7033). Ruggedized and reliable, these tubes are particularly suited for these typical applications:

Airborne	Shipboard	Ground
Weather radar	Sonar long-memory displays	Slow-scan television
Search Navigation	Marine displays	Storage instrumentation
Terrain Avoidance	Sonar devices displays	

Write today for complete data on these new Machlett Direct View Storage Tubes.

MACHLETT **The Machlett Laboratories, Inc.** Springdale, Connecticut

a subsidiary of Raytheon Company

ML-8087 Precision

Scan Conversion Tube
Fast Erase — High Resolution

The Machlett Laboratories, Inc. announces a new precision manufactured Scan Conversion Storage tube, the ML-8087. Successor to the Machlett made 403X type tubes, which have seen over one million hours use in airways control service, the ML-8087 provides these principal advantages and important features:

1. High resolution: a minimum of 180 range rings/diameter at 50% amplitude modulation; equivalent to 900 TV lines.
2. Fast erase: less than 2 seconds erase cycle to reduce stored information to noise level.
3. Wide storage range: to meet FAA 1213b specification and beyond.
4. High signal/noise ratio, typically 80:1 (peak signal to rms noise).
5. Rapid set-up time: A few minutes installation is all that is required to adjust tube for optimum operation. No need for critical dynamic focussing of electron beams.
6. No variation of output signal with size of written area.
7. Only simple video circuits are needed for readout.

Available now from The Machlett Laboratories, Inc. . . . send for complete data on the ML-8087.

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A division of Raytheon Company
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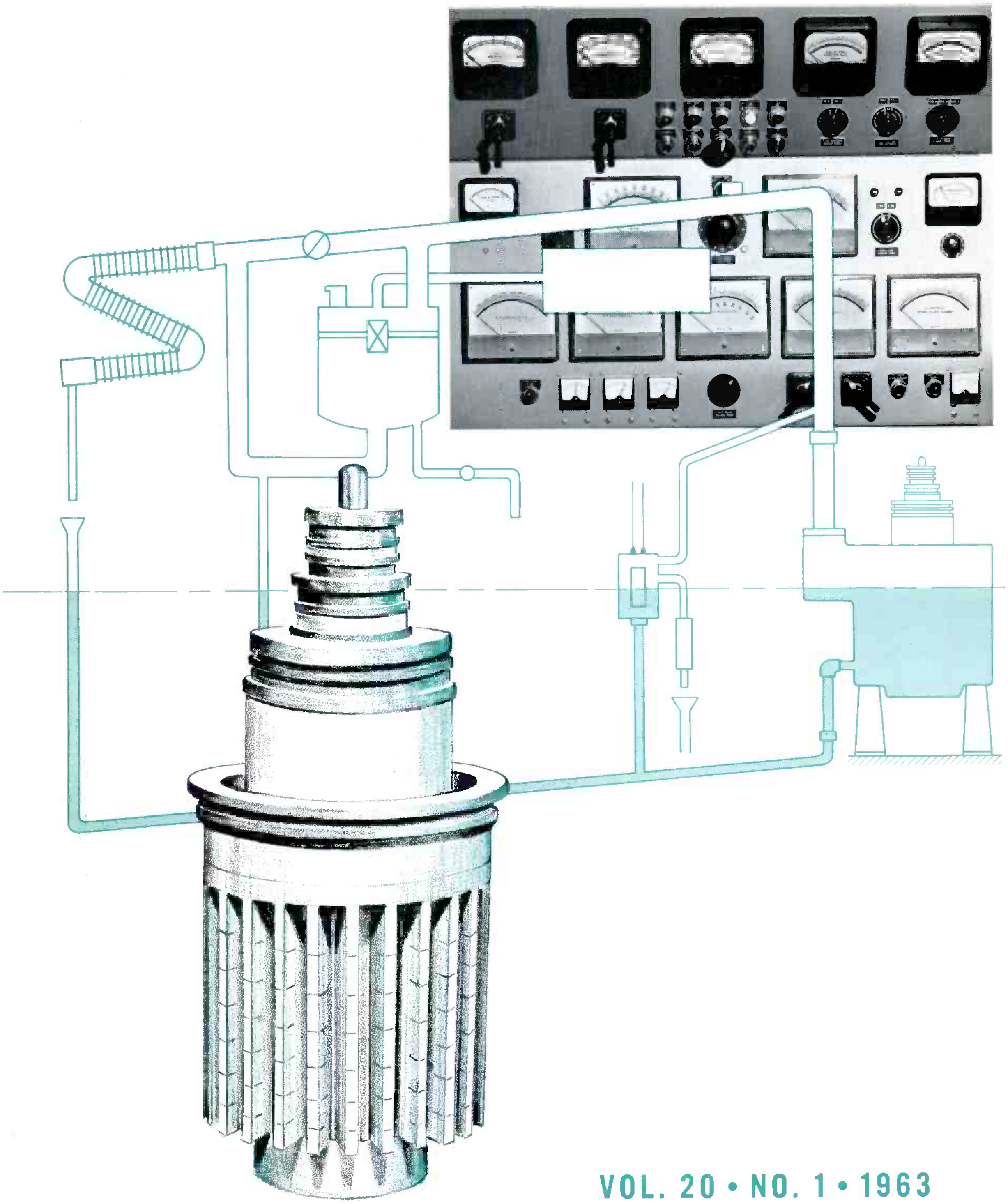

VOL. 20 • NO. 1 • 1963

ML-7351A

High Sensitivity Tipless Vidicon

Highest sensitivity—less than 0.05 Ft. C. faceplate illumination required.

The Machlett ML-7351A tipless vidicon offers the highest sensitivity of any commercially available vidicon. High sensitivity permits use of tube with less than 0.05 foot candles illumination incident on faceplate. This corresponds to an average scene illumination of less than 2.5 foot candles when using an f/2.0 lens.

Lower dark current—for slow scan television

Operating at sensitivity equivalent to that of other high sensitivity vidicons, the ML-7351A requires a lower dark current. In slow scan systems, therefore, the lower dark current pedestal permits greater signal current accommodation by the amplifier. For example, at ASA 1200, the ML-7351A requires a dark current of only 0.05 ua, approximately ¼ that of comparable tubes.

High radiant sensitivity in the red region

High sensitivity in the extreme red region permits advantageous use of the ML-7351A in viewing incandescent materials, jet exhausts and other extreme temperature phenomena.

Resolution . . .
500 lines to 800 lines depending on focus electrode potential.

Signal decay rate . . .
About half that of standard light sensitive vidicons.

Write today for the complete data on the ML-7351A tipless vidicon.

THE MACHLETT LABORATORIES, INC.

SPRINGDALE, CONNECTICUT

MACHLETT

An Affiliate of Raytheon Company

CATHODE PRESS

Vol. 20, No. 1, 1963

Editor, *Richard N. Rose*

Art Director, *Edward J. Bulger*

IN THIS ISSUE

ANNOUNCING A NEW SECTION IN CATHODE PRESS

COVER . . . is a representation of the subject of the initial article in this issue: the 1.2 MW Test Unit, emphasizing one of its test capabilities — vapor cooling.

Product Lines represented in this issue:

Large Power Tubes
Small Power Tubes
Photosensitive, Storage & Display Tubes

Published by:
The Machlett Laboratories, Inc.
An Affiliate of Raytheon Co.
Springdale, Connecticut

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MARCH 1963

Editor's Note:

With the acquisition of its new 1.2MW power tube test unit, The Machlett Laboratories has consolidated the testing of its largest power triodes (forced-air-cooled, water-cooled, and vapor-cooled) in a single, highly efficient device. In addition Machlett has established the means for future development into even higher power tubes than are now offered (600kW input) and can take new developmental steps with the full assurance that these tubes-to-be will be qualified for performance at their highest ratings. Other large test sets now in operation include a 100kV-100mA pulse tube test set and a 200kV-200mA unit (Cathode Press Vol. 19, No. 1, 1962, "Hard Pulse Modulator Test Facility: 200kV-200mA Capability") in addition to its already extensive power tube test equipment, place Machlett in a uniquely strong position to evaluate and rate its tubes.

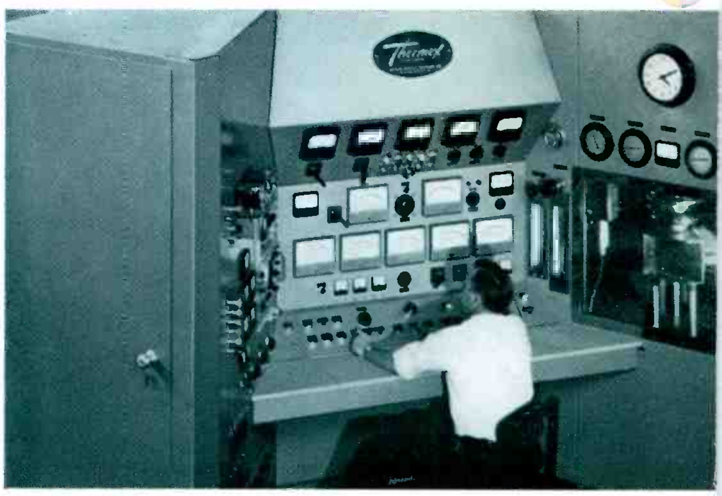
• • •

Design, Engineering and Construction of the

In the following article, Mr. T. L. Wilson, Chief Engineer, Electronics, Votator Division, Chemetron Corporation, describes the Machlett 1.2 MW test set as seen from the point of view of the designer translating the customer's instructions into fact. Mr. Wilson discusses the need for one man operation, the consequent simplification of controls and the considerable attention given to proper layout and instrumentation of the control panel. The electronic/electrical fundamentals of the unit, as outlined, reflect the need for easily controlled, continuously variable drive and the use of an infinitely variable load impedance system. Physical provisions for tube installation and test, with resulting considerations given for maintenance of proper electrical conditions (terminal connections, provision for maximum decoupling between driver and neutralizing circuit among others) are developed in addition to matters relating to tube water load, tube cooling, power supply requirements and fault protection.

The basic statistics of the 1.2MW unit reflect its considerable magnitude.

• Plate Supply Volts	0-30 kVdc	Amps 0 —40a
• RF Bias Supply Volts	0-4 kVdc	Amps 10a
• Bias Supply (peak emission & static test) Volts	0.5 kVdc	Amps 20 ma
• Frequency	13.56 Mc	



Mr. T. L. WILSON

Mr. T. L. Wilson is a native of Salt Lake City and an electrical engineering graduate of the University of Utah. He was with RCA in Camden, N. J. and Federal Telephone and Radio Company, Newark, N. J. before joining Thermex, now a Department of the Votator Division.

Votator, a division and major affiliate of the Chemetron Corporation is basically a manufacturer of process equipment. Through its pioneering line of "Thermex" dielectric heating equipment, Thermex and Machlett have been jointly associated for many years.*

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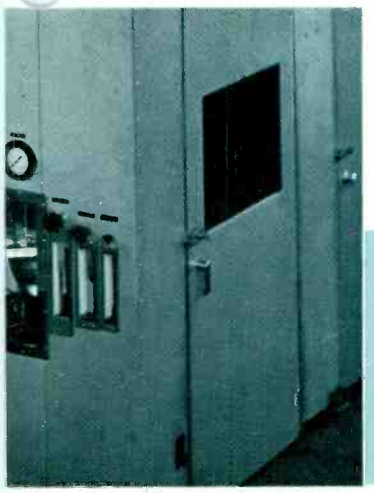
'Thermex' High Frequency Tube Tester

By T. L. WILSON, Chief Engineer, Electronics, Votator Division, Chemetron Corporation



Introduction

"We need a high-frequency test set sufficiently stable to handle a wide variety of tubes under various load conditions, to make all the necessary production tests plus special engineering tests for the 'odd-ball' job, to handle powers from 50 kilowatts to 1.2 megawatts, to use ordinary city water directly in the cooling system, to put no unusual burdens of short circuits on the power lines, although it is expected to operate a crowbar as much as 2,000 times per week, and to do all this without any danger of radio interference or X-radiation."

This in essence was the assignment given to the Votator Division of Chemetron Corporation by The Machlett Laboratories, an affiliate of the Raytheon Company. After many months of detailed planning, building and testing in Louisville, Ky., plus installation and more testing at Springdale, Conn., a test set that meets these exacting requirements and more is a reality and is in daily use to ensure the production of increasingly reliable tubes for a large variety of uses.

The compact new unit, which covers a floor area of 255 square feet, is designated a Thermex High Frequency Tube Tester. "Thermex" is Chemetron's trade-mark for the Votator Division's line of high-frequency dielectric heating equipment and related electronic products. It is an amplifier type unit that can test the most powerful modern tubes in a circuit very similar to that in which they will actually be used; it also provides absolute stability of frequency for greater control of test conditions than more common oscillator-type test systems.

At 1.2 megawatts input, the new unit is believed to be the most powerful high-frequency tube test set in operation at this time. A companion article in a subsequent issue of the CATHODE PRESS by Machlett's Mr. Raymond C. Black describes the uses of the equipment and reasons for the exacting specifications. This article deals with the design, engineering, and construction of the test set.

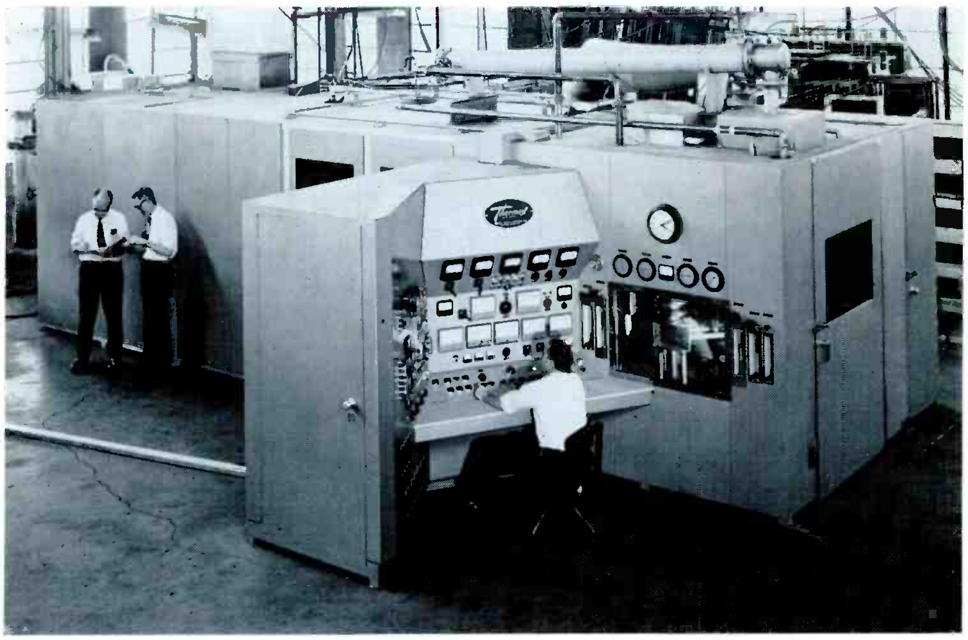


Figure 1 — Overall view of the 1.2 MW high frequency tube tester designed and constructed by the Votator Division of the Chemetron Corporation for The Machlett Laboratories, Inc.

Size and Shape

Machlett's specifications were written in such a manner that the over-all layout of the test set was left to the Votator Division's Thermex engineers who presented drawings and other data outlining their plan of attack. Among other early steps, a life-size mock-up of the main control panel was constructed for approval by Machlett.

The drawing of Figure 2 shows a plan view outlining the general shape of the equipment and the photograph of Figure 1, made at the Votator plant in Louisville, gives an over-all concept of the test set. As indicated in these figures the general shape is similar to a letter T, with the distances being 17′6″ across the top and 29′ from end to end.

The entire equipment was constructed to be broken down into a minimum number of sections, and all but the fragile and very heavy components were shipped from Louisville in place in their cabinets. Scheduling arrivals at the plant site in proper order to permit logical unloading and movement into the building without the necessity of moving one section past another greatly simplified the installation of the equipment.

One Man Operation

Operator convenience and ease of accessibility to all components were two of the major considerations that dominated the layout discussions. For economy in normal production work it was essential that only one operator be required to accomplish all of the necessary operations of vacuum tube production test work. Yet the equipment had to be built with the knowledge that at many times the performance of special tests on developmental models of tubes would make it desirable to have space for several observers near the operating position. Furthermore, although the testing of tubes is a task which requires skill and judgment on the part of the operator, the fewer control adjustments necessary for a given test, the fewer the costly mistakes. Therefore simplicity was an additional important consideration. It may seem contradictory to call a unit as large and complex as this test set a simple device. Yet when it is broken down into separate components and functions, it is not really very complicated. Reference to Figure 2 during the reading of the next few paragraphs will help in understanding the description and comments.

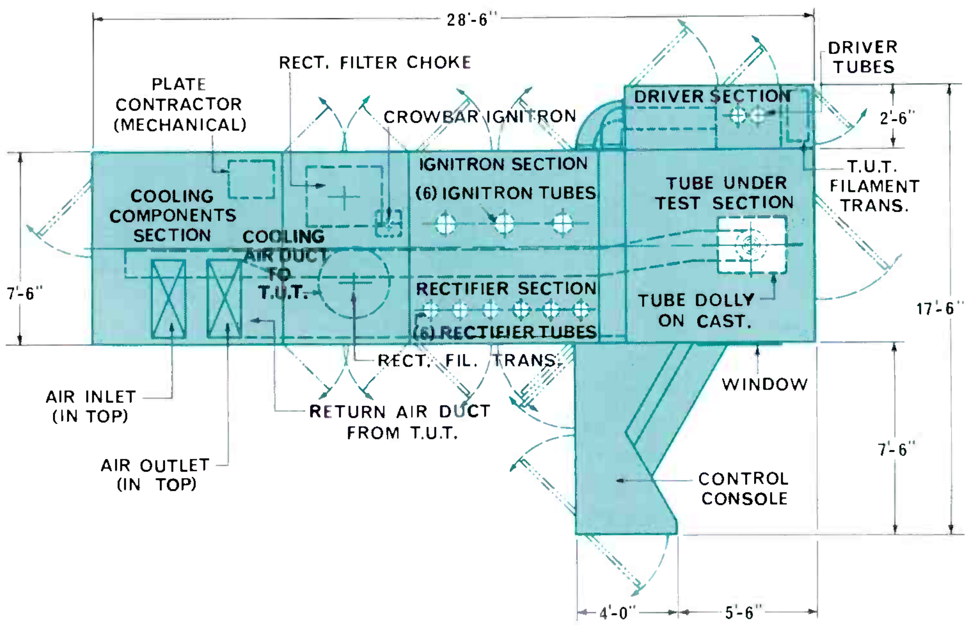


Figure 2 — Plan view of 1.2 MW test unit outlining general shape.

Control Panel

During early design stages the control panel received a great deal of attention. The full scale mock-up enabled the designers to visualize the various operations the test man would have to perform and to place the controls and meters at a convenient location for him. For example, it was essential that the tube under test and the supervisory metering equipment be readily observed almost simultaneously. For this reason Machlett wisely specified large meters with mirror scales in many instances. Also, the final layout (Figure 3) located a large 30" x 36" viewing window for the tube under test to the right of the operator and made it part of one wing of an "organ console" type control panel (Figure 4). Thus the operator, positioned at an angle to the front of the unit, merely turns his head to view either the metering equipment or the tube itself. Meters which had to be located above convenient eye level for space reasons are tilted to let him look directly at the scales. Switches for changing the ranges of the instruments are usually located near the instruments themselves. A few of the less used control switches are also located on the upper portion of the panel.

Having one wing of the control console also serve as the wall of the tube under test compartment made it logical to have the water and air metering equipment located on this same wing of the console. This greatly simplified the piping problems and shortened the capillary tubes to the various thermometers. The temperature of incoming air and water and the temperature of the water leaving the load and the tube are measured by separate instruments. The incoming air pressure is also measured. Water flow in the anode circuit of the water cooled tubes and in the water load is measured by rotameters, two in each circuit, so that an accurate range of rotameters is available for the full size range of tubes and powers being handled. A fifth rotameter measures the water flow in a load that can be connected to the driver section of the test set.

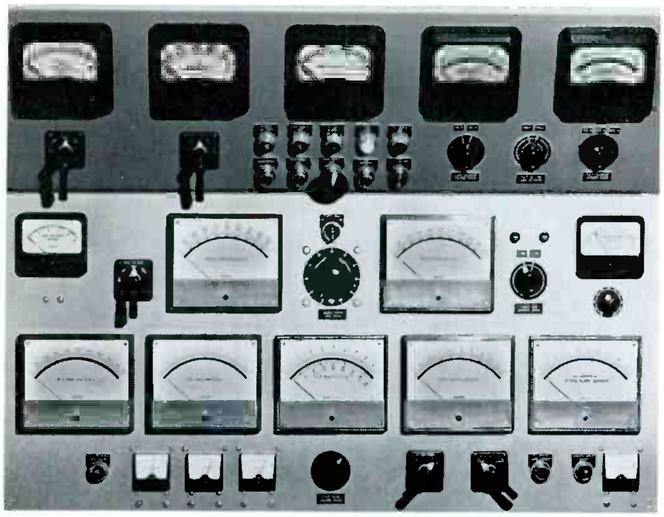


Figure 3 — Control panel showing large face meters easily viewed by operator.

Figure 4 — Control panel area showing ease with which test operator can view both tube under test and control panel metering.

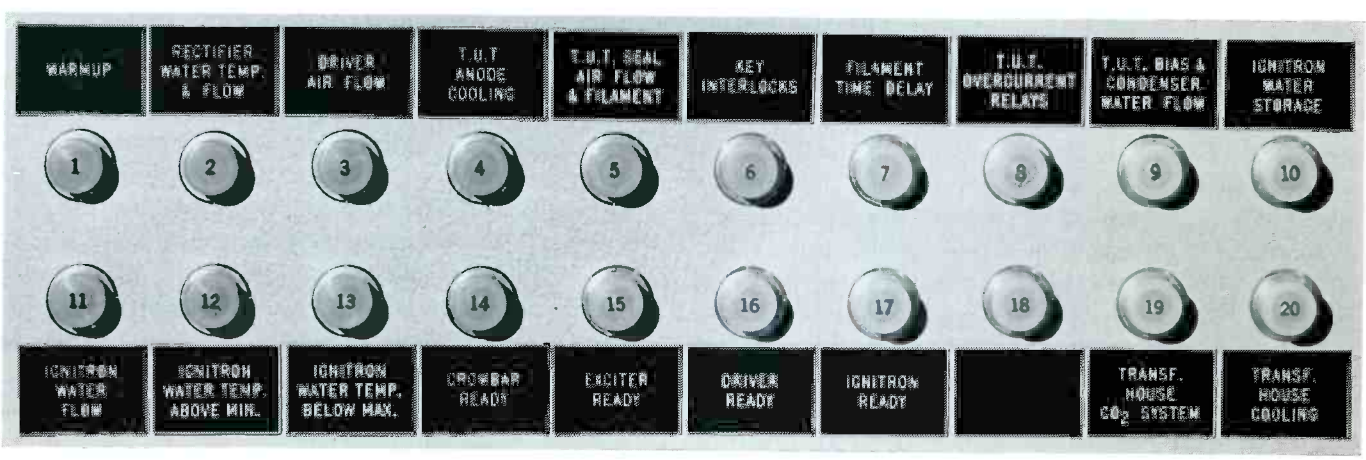
The main controls required by the operator are located on a lower tilted panel that is just above a desk space on which he may place his test sheets and other reference material. This places most of the required switches and controls for the final amplifier at his finger tips, with no need to raise his elbows from the desk top. The main tuning controls and drive control for the equipment are handled by the left hand while the filament and plate voltage controls, on-off switches and other necessary switches are on the right. Major meters indicating plate and grid voltages and currents are directly in front of the operator.

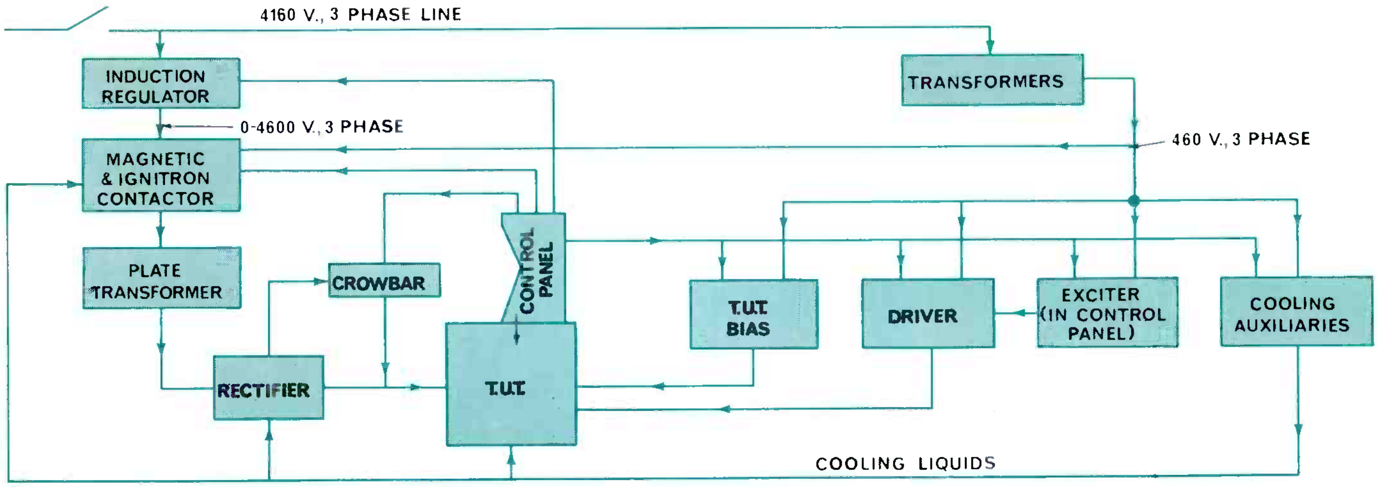
Controls for the low powered rf stages from the crystal oscillator through the driver stage are located on the left wing of the console. Some of these are manually operated while others are motor driven. All motor-driven controls in the test set have position indicators. The left wing of the control console also has the "home" or "storage" position for all the door keys, an oscilloscope for noting wave shapes and measuring peak emission of the tubes, an rf voltmeter used in checking the rf potentials of certain circuits and in neutralizing procedures, and a rather comprehensive system of lights which indicate the conditions of various portions of the circuit (Figure 5). These lights are very useful in analyzing the status of the control circuit and have saved many hours of trouble-shooting in design testing and early stages of tube testing.

Block Diagram

Figure 6 shows an electrical block schematic diagram of the equipment. An assigned frequency band for industrial,

Figure 5 — Control circuit status lights for analysis of conditions in various portions of the circuit.





ARROWS INDICATE DIRECTION OF POWER OR CONTROL

Figure 6 — Electrical block diagram of 1.2 MW test unit.

scientific and medical equipment, 13.56 megacycles, was selected as the frequency for this unit. However, as is well known, some of the harmonics of this frequency do not lie in the frequency bands assigned for the ISM services and even though the equipment was to be well shielded, it was possible that a harmonic could be troublesome. Therefore, a narrow bank on either side of this frequency was also specified so that slight shifts of frequency could be made if desired.

A crystal oscillator operating at half frequency feeds a tetrode buffer amplifier which also acts as a frequency doubler. This in turn supplies drive to an intermediate power amplifier utilizing a tetrode tube. The screen voltage of the buffer-doubler amplifier was made variable so that the drive power to the tube under test could be readily controlled by a single knob on the control operator's panel. This also required operating the subsequent stages in a Class A-B type operation during some of the low powered tests. However, no great attempt at linearity was felt necessary.

The actual equipment for the low powered stages is located directly behind the left wing of the control panel. A coaxial line is used to transmit the rf power to the driver stage which is located on the opposite side of the tube under test compartment from the control panel. This stage, using a pair of Machlett 7007 tubes in parallel, supplies the main driving power for all the tubes under test (Figure 7). The tuning of the driver is motor-driven from controls on the left wing of the console. Metering circuits for all of the low powered rf stages including the driver are also on this panel.

The driver is enclosed in its own cabinet, access to which is gained through three full height doors so that each component is within easy reach for maintenance.

The driver cabinet, in addition to containing the necessary power supplies for its own operation, also contains the bias power supply and the filament transformer for the adjacent tube-under-test compartment.

Tube-Under-Test Compartment

Most designs of power amplifiers require the use of only one type of tube and one value of load impedance although several frequencies of operation are usually required. In Machlett's Thermex test set there is only one narrow band of frequency operation, but the set must handle at least five basic tube designs and a large number of load impedances so that the load on the five types of tubes can be varied from near zero load to considerably overloaded conditions. The variation in load impedance is an "infinitely variable" type system.

Inasmuch as the five basic tube designs also required three types of cooling, namely water, air, and vapor, considerable mechanical as well as electrical flexibility, was required of the design. In addition to the normal amplifying tests, during which the power handling abilities of the tube are determined, several static type tests are also performed with the test set. These include measurement of peak emission, gas current, amplification factor, filament characteristics, and others.

For ease of mechanical handling, as well as flexibility to adapt to the various types of tubes, wheeled carriages or dollies were constructed (Figure 8). Three of these were made, one for each of the three types of cooling to be employed. Each dolly has a basic insulated stand to which the various tube sockets and their adapters are mounted. The adapters for the various tubes, of course, include the connectors for the filament and grid terminals in addition to the cooling socket. The dollies are easily placed in position to receive the various connections required for the tests. A

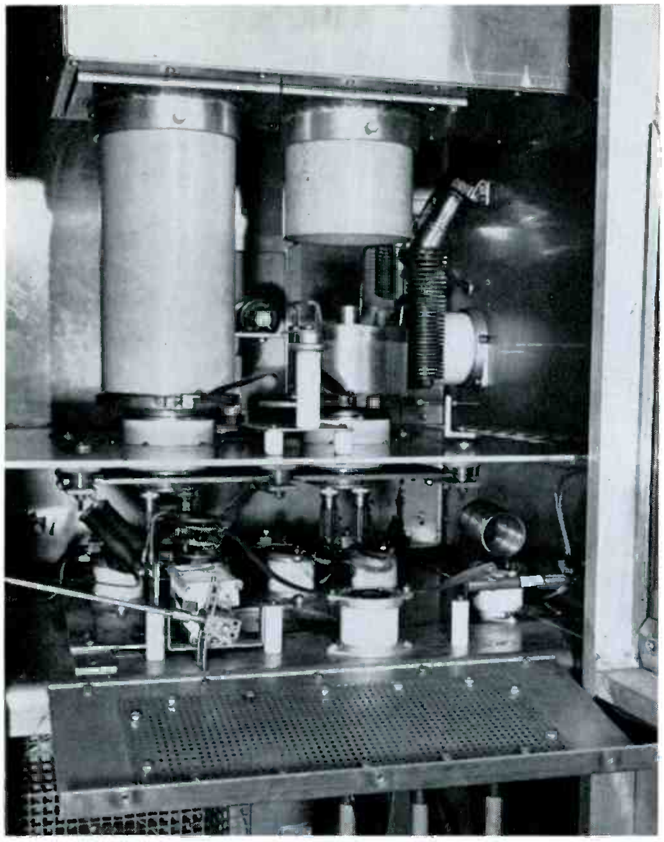


Figure 7 — ML-7007 tetrodes supply main driving power for all tubes under test.

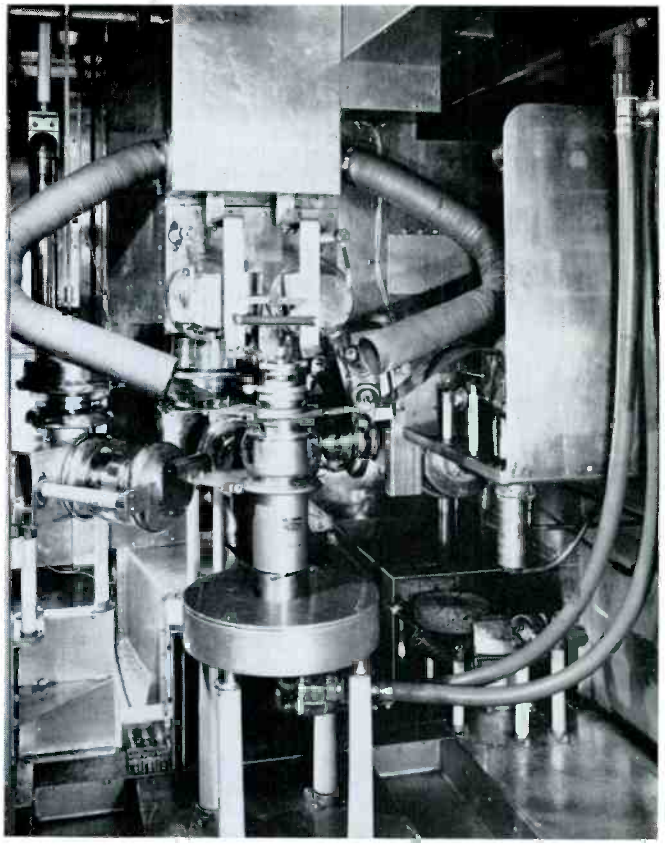


Figure 8 — Test bay showing tube under test on dolly and its simplified cooling connections.

portion of the tube-under-test compartment floor was lowered to the building floor level to facilitate moving the dollies in and out.

Cooling connections are easily made. The air cooled tube dolly is merely pushed against the main incoming air duct in the amplifier to complete the air connection. For water cooled tubes quick connecting fittings on flexible hoses are used so that only a few seconds are required for making the water connections. Water spillage is kept to a minimum and a floor drain carries away any water that does escape. Connections for the vapor cooled tubes are somewhat more complicated by the need to attach the steam outlet chimney that conducts the vapor from the boiler upward to the condensing system mounted on top of the compartment. From this point the condensed vapors drain back into the tube socket where they may again be vaporized.

Accessibility vs. Stability

Although dollies were provided for moving the tubes to be tested into the test position, it is desirable in many instances to be able to change the tube without removing the dolly from its test position. This limited the amount of equipment that could be placed directly above the tube under test. Furthermore, for stability reasons, certain portions of the circuit had to be shielded from other portions. Thus, it was desirable to have a rear access door, reached by way of the ignitron contactor compartment, as well as a front access door to the tube-under-test compartment. For mechanical flexibility in handling the various sizes and types of tubes, the otherwise desirable short leads usually found in high frequency, high powered equipment were somewhat compromised. For example, a coaxial arrangement of filament and grid circuits was considered but abandoned due to the difficulties in changing tubes as well as adapting to various types of tubes. The various leads connecting the tubes to the circuits were made as wide as possible in order to reduce the difficulties inherent with this compromise. To permit rolling the dollies in and out, 180 degrees of the horizontal space around the tubes had to be left clear and was not available for circuitry. The side closest to the control panel also had to be kept relatively free of large circuit components in order to provide an unobstructed view of the tube from the operator's position.

To provide maximum decoupling between the driver circuit and the neutralizing circuit, in addition to the mechanical considerations mentioned above, the driver circuit was placed on the far side of the tube-under-test compartment from the control console. This placed the neutralizing circuit, inherently smaller than the driver, near the operator's viewing window, but to the operator's left, i.e. to the rear of the tube-under-test compartment (see Figure 4). The main tank and load circuits were placed between the neutralizing circuit and the driver circuit and to the rear of the tube under test. Necessary shields were included to isolate the circuits from each other.

A coil type neutralizing circuit was chosen because of its simplicity as well as its relatively lower voltage requirements for the tank capacitor components. This places a parallel resonant circuit between the plate and grid of the tube so that there is a high resistive impedance between these two elements rather than the usual low capacitive impedance. It was found that this choice was adequate inasmuch as it is possible to reduce the drive voltage to zero, once the circuit is properly neutralized and under Class C conditions for many tube types and plate voltages.

The tank circuit utilizes a water-cooled inductance and a variable vacuum condenser which is also water-cooled. Another water-cooled variable vacuum condenser is used in the load circuit. The coupling capacity between the two circuits is not directly water-cooled (its mounting connectors are) nor adjustable under power, although it is a variable vacuum condenser.

Water Load

In achieving the specified capability of dissipating 800 kilowatts continuously, two loads were constructed. These were the same type as have been used for many years for calorimetrically measuring the power output of dielectric heaters. These loads are simple devices wherein the water itself conducts the rf current. Each load consists of a metal tank through which water is circulated, and these tanks are connected in series. Inasmuch as the tanks are near ground potential only short hose connections and metal pipes are required. The water load includes an electrode which is immersed in the tank water and is insulated from the tank itself. The inner electrode is connected to the hot terminal of the generator and conducts the current to the water. The flow rate and temperature rise of the water as it passes through the load are measured and calculations made to indicate the power output. It is usual to run the water flow at a convenient rate so that a full integral number of kilowatts per degree temperature rise is obtained. Then multiplying the temperature rise by the integral number gives the power output without the need of slide rule calculations.

The water load is made part of a parallel resonant circuit which is capacitively coupled to the main amplifier tank circuit. The load circuit is not normally tuned to exact resonance and the tuning adjustment is used to determine the amount of load placed on the amplifier. This does not unduly detune the amplifier, although it is necessary to maintain surveillance on the amplifier tuning as the load adjustment is made. The tuning and the load control switches are located close enough to each other so that the operator needs only one hand to make both adjustments. Using this load circuit arrangement it has been possible to adjust the load from that required by the largest tube operating at high current and low voltage to that needed by the smallest tube at a fraction of its normal capabilities.

Cooling

For proper measurement of air flow to the air cooled tubes, and particularly for calibration of these measurements, it was desirable to have a long air duct between the blower and the tube under test so that the air flow would be laminar and stable at the point of measurement. This made it logical to have the cooling section as the rearmost compartment of the entire equipment. The cooling section, in addition to the large blower for air cooled versions of the tubes, contains another blower for moving air through the various cabinets for general cooling. Filters and a dampering system automatically filter and mix outdoor air with the returning air from the equipment to keep the interior at the desired temperature at all seasons of the year.

The cooling compartment also contains 3 water pumps, one for the tube under test and rectifier tubes, one for the water load, and one for the ignitron contactor. The ignitron contactor has its own cooling system to maintain the ignitron cathodes at the proper temperature under all conditions, independent of the load on the rest of the cooling system. Ordinary city water is used for cooling the tubes directly. No distilled water is used in the water cooling systems. City water is recirculated throughout the equipment with enough cool water being taken into the system to keep the average temperature of the water at a safe value. Automatic temperature control valves are used for this purpose.

The load resistor for the main rf bias supply, which also acts as the grid leak for the tube under test, is located in the return air duct just above the main cabinet cooling blower. This eliminates considerable heat from the rest of the equipment inasmuch as the air is discharged over the grid leak resistors. The mechanical magnetic contactor, included in the circuit in addition to the ignitron contactor, is also located in the cooling section compartment.

In both the rectifier and the tube-under-test cooling system, electrolytic targets were placed at strategic points to avoid electrolysis of the metal portions of tube sockets. In the case of the tube under test, the electrolytic target is at the dc potential of the anode of the tube under test, but a silicone flexible hose was placed between the electrolytic target and the actual tube under test. This flexible hose handles the major portion of the rf voltage drop so that only a small portion of the high frequency anode voltage is placed on the plastic piping.

Rectifier and Ignitron Compartment

The intervening space between the cooling compartment and the tube-under-test compartment is used for the main high voltage rectifier and its associated filter, the ignitron contactor, and crowbar (Figure 9). Access to these sections is through full height doors on either side of the unit, with large glass windows for permitting visual inspection of the interiors during operation. The rectifier circuit utilizes six high vacuum type rectifiers in a three phase series type of circuit. Other than the use of rigid plastic piping in the cooling hose reels, the use of high vacuum rectifier tubes, and the necessity of increasing the size of the plate transformers for reasons described below, this circuit is quite standard. A small filter is included to smooth the ripple inherent in rectified dc to a sufficiently low value for test purposes.

The other power supplies for the entire equipment are rather straight-forward. All amplifier tubes have fixed bias supplies so that the entire equipment can be keyed as in a telegraph transmitter. This was actually done at low power levels as a test of equipment stability. The high voltage which, as previously mentioned, uses high-vacuum tubes necessitated by the high voltages which were called for, also includes an ignitron contactor, the reasons for which are described below.

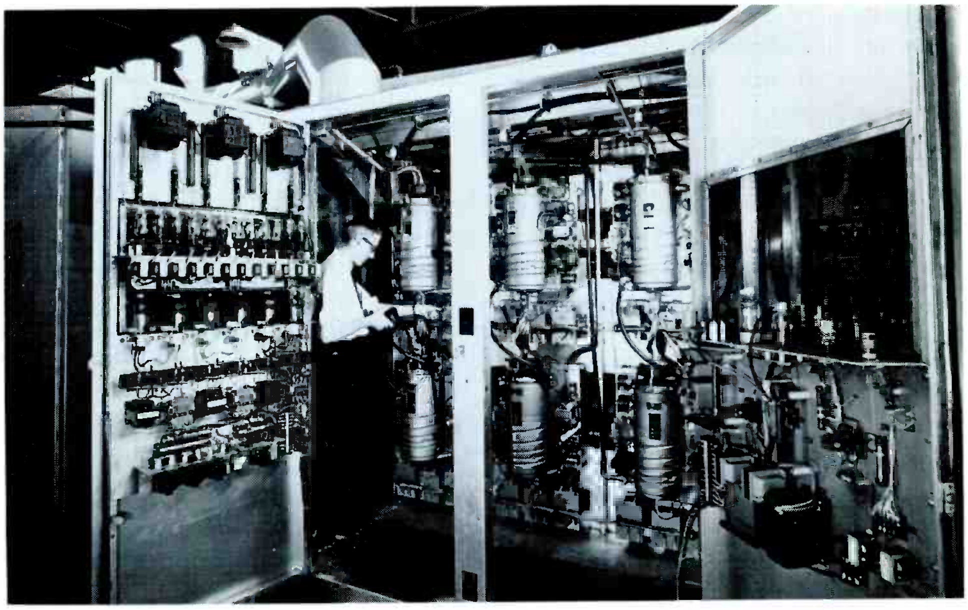
Outdoor Components

The very heavy components such as the main plate transformers, the induction regulator, the series line chokes, etc., were specified so they could be placed in an unheated building. The transformers and line chokes have been placed in a specially constructed steel house to provide shielding which prevents radio frequency interference. The induction regulator for controlling the plate voltage from zero to 30,000 was placed out of doors. These items were located some 300 feet away from the main test set where space was available.

X-Ray Protection

In general, the equipment has a steel framework covered with 1/8″ steel panels. Where radio frequency interference problems required good conductivity between sheets of metal, an aluminum liner was used. The steel, in addition to providing necessary structural strength and mechanical protection, also provided very adequate protection against X-radiation which comes from vacuum tubes when operated at voltages in excess of 20,000 volts. At 30 kilovolts, the highest required voltage, X-rays are of the soft variety that do not have great penetrating power. However, they are dangerous if allowed to escape into the areas containing personnel. Where windows in the steel cabinet structure were required, leaded glass was installed to complete the X-radiation protection. These precautions reduced the X-radiation to an almost immeasurable level when the doors were closed (very much less than 0.1 milliroentgen per hour). However, with the doors open the radiation was measured to be 115 milliroentgens per hour with the tube operating at 30 kVdc. The radio frequency shielding was also checked and was found to be good while the equipment was at the Votator plant. Preliminary checks made at the final installation site indicate the radio frequency radiation is well within the requirements of the Federal Communications Commission.

Figure 9 — Ignition compartment. Carl Ellsworth, Votator Division, is shown making an electrical check.



Interesting Problems

In addition to the interesting problems connected with the design of the tube-under-test compartment there were other unusual problems encountered. These were largely due to the high power requirements of the equipment and are generally electrical in nature.

Power Line Protection

For example, the utility company that was to supply power for operating this equipment was concerned about the high number of short circuits that could be experienced by the power line. In the development of new tube types it is essential that a reliable maximum voltage rating be determined. In making such an evaluation it is necessary to check tube arcing vs. dc plate voltage and power output on a number of tubes. To make a satisfactory analysis, the tubes must be run considerably in excess of the ratings that are ultimately given on the technical data sheet for the tube type. During such experimental work the tube will be subjected to many internal flash arcs. During the routine "seasoning" portion of production tube testing, plate voltages are also higher than those given in the published ratings, and the tubes will be subjected to internal arcs. These arcs place a short circuit across the high voltage dc power supply and permit a large amount of energy to be discharged into the tube under test. To limit the amount of energy a crowbar device was included. It places a second and lower impedance short circuit on the output terminals of the dc supply, thus short circuiting the currents which may flow in the internal arc of the tube under test. In order to limit the amount of damage to the tube under test, Machlett requested that the crowbar device operate in approximately 10 microseconds and not damage a small thin section of aluminum foil placed between the high voltage dc bus and ground. Such a crowbar device was successfully constructed.

When the utility company learned that such a device would be installed they questioned their ability to allow this equipment to be connected to their power lines. As originally conceived, with normal reactance in the magnetic components of the power supply it would not be unusual for a 12.000 kVA fault to be applied to the incoming power lines, and under some conditions, it could be even higher. This much of a suddenly applied (or suddenly removed) load on the incoming system would cause a serious voltage dip each time the short circuit was applied. These voltage dips would cause flickering lights and television picture difficulties in nearby residential areas and possible drop-out of contactors and circuit breakers with the associated equipment or plant shut-downs in nearby industrial plants. Any power system is subject to currents of this magnitude once in a while, but 2,000 of them per week were considered unbearable. The utility company requested that the suddenly applied or removed load be no more than the full load kVA of the equipment. This permitted no increase in load current under many short circuit conditions. Of course this request was technically unfeasible.

Three steps obviated this problem. First, negotiation with the utility company produced a tentative agreement which raised the limit of suddenly applied or dropped load to 5,000 kVA. Second, sufficient reactance was included in the various transformers and line reactors in the incoming line so that the short circuit kVA would be limited to the 5,000 value. The line reactors were located alongside the high voltage transformers in the outdoor shielded enclosure. Third, a high speed contactor was included that removes the short circuit from the utility line in about one-half cycle. This was accomplished through use of an ignitron contactor system which was triggered to operate or open the circuit at the same time the crowbar was triggered to place a short circuit across the high voltage bus. Thus the crowbar removes the voltage from the tube under test in approximately 10 microseconds and the ignitron contactor removes the short circuit from the power lines in less than 10 milliseconds (about one-half cycle). This high speed removal of the short from the power line is too fast for visual observation of flicker even in fluorescent lights and is much faster than magnetic devices such as contactors and relays. In the several weeks of operation of the equipment during initial tests and operation no complaints have been received although it is known that the crowbar and ignitron contactor have both functioned several thousand times.

High Voltage Transformers

The inclusion of the high reactance in the power system feeding the equipment caused unexpected difficulty in specifying the size of the high voltage transformer. In normal power supply design, even in those for as large as 300 kilowatts output, the reactance of the supply line is usually found to be sufficiently low that an increase of 5% in transformer voltage and kVA above the dc requirements is sufficient. However, in the power supply for the 1.2 megawatt tube tester, where the large amount of current limitation had to be included for the reasons described above, the kVA rating of the plate transformer had to be increased from 1.2 to 1.7 MVA, an increase of 42% instead of the usual 5% commonly allowed. Resulting voltage regulation problems were easily taken care of by an induction regulator already specified for the equipment.

The increase in kVA of the plate transformer bank was required by the fact that inductance tends to cause current to flow even after the voltage which originally caused the current has reached zero. This creates an overlap of current conduction between the various tubes in the rectifier such that for short intervals of time two phases are "short circuited" during each cycle. The result is an increase in voltage drop in the reactance of the line feeding the rectifier bank, called the commutation reactance, and requires a higher voltage from the high voltage transformer to com-

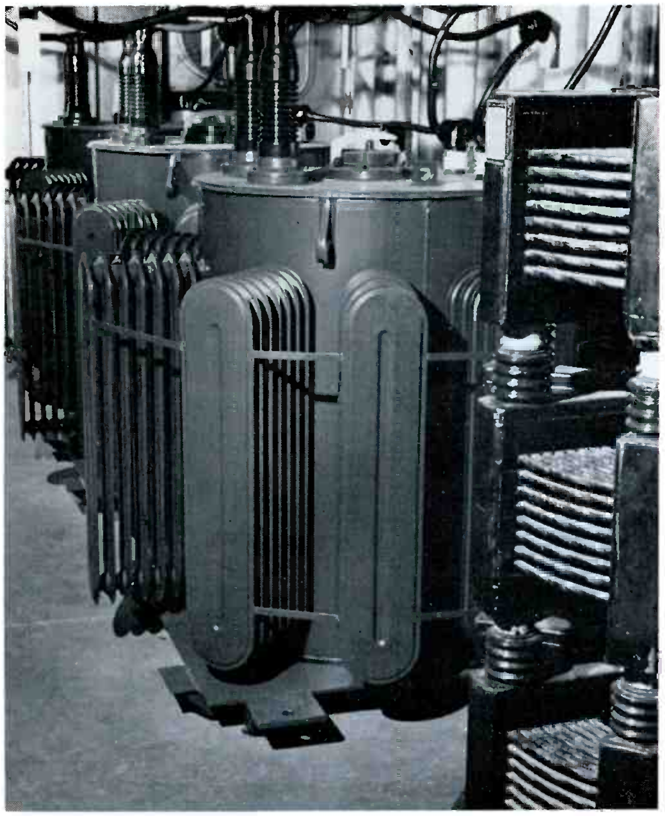


Figure 10 — Power supply transformers and line chokes, shown here, for 1.2 MW test unit are located in a steel house to prevent rf interference.

pensate for the additional drop. The current rating of the transformer remains constant although the kVA rating is raised by the additional voltage requirement.

Credits

As in any project of this nature, the successful conclusion has been the result of cooperative effort not only between Machlett and Votator but also between the individual engineers immediately involved. During the construction phases, where engineering information was not complete, close cooperation of the manufacturing facility with the designing facility was required. Such cooperation was given by all concerned with this project. Some of the people carrying the largest share of the burden include R. C. Black of Machlett Laboratories who was advised by Dan Kudola and C. V. Weden (now Project Engineer, Power Grid Tube Laboratory at Eitel-McCullough) of the Machlett engineering staff. For the Votator Division Carl E. Ellsworth was assigned the job as his major effort and followed the job from start to finish. He was assisted in various stages by Richard R. Moore and Willard H. Hickok of the Votator engineering staff, plus Rufus E. Smith and James E. Marshall of the Votator manufacturing staff. To these men goes a lion's share of the credit for the success of the project.

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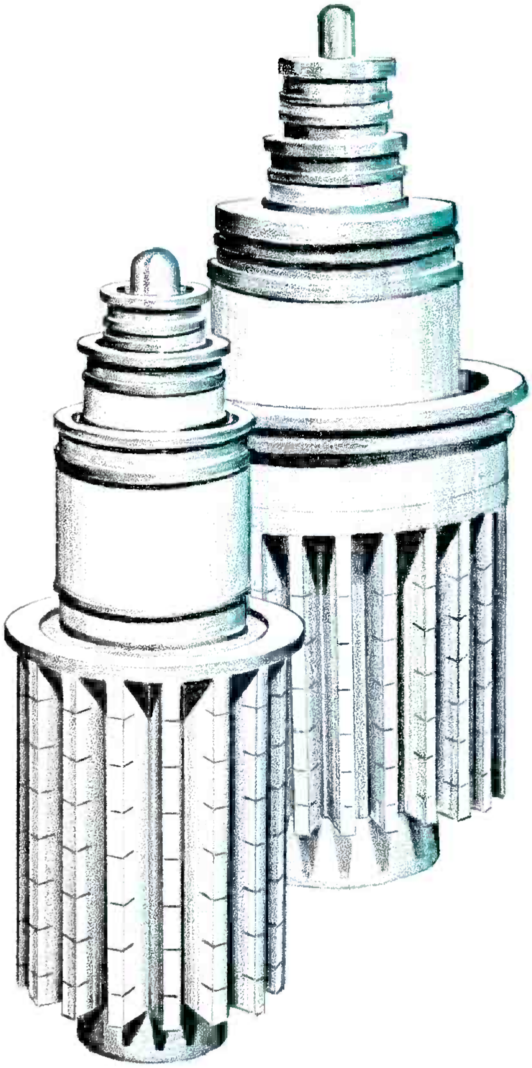
Supplementary Advantages of Vapor Cooling:

Recovery of Heat

About half of the input power into a broadcast transmitter of high efficiency has to be removed as heat from the anodes of the power tubes in the final stages. In air cooled and also in water cooled tubes this power is lost. In water cooled tubes, for example, the temperature of the outgoing water is too low to be of any use. In vapor cooled tubes the same amount of heat has to be removed; however it is in the form of steam, which is directed into a heat exchanger. It now becomes feasible and rather simple, using a water cooled heat-exchanger, to bring the water in a secondary circuit to about 95°C, and use the water for central heating of the broadcast station and adjoining staff homes. Very hot water lends itself well to heat storage; thus, in many installations a hot water storage tank is provided, and at nighttime, when the transmitter might be shut down, central heating may be



Introduction

Cooling of high power electron tubes by the vapor cooling process has been in existence for more than 10 years in Europe, and has during the last few years found interest and application in this country also. The first major installation in America using this highly efficient method was the 250kW Voice of America transmitter, constructed in Greenville, N. C. by the General Electric Company[1]. Each transmitter employs five Machlett ML-7482 vapor cooled tubes (Figure 1), two in the final amplifier, one in the intermediate power amplifier and two in the modulator. All tubes operate into one common cooling system.

Efficient cooling of high power tubes by ebullition of water or other liquids (with subsequent high anode dissipation levels) was developed in France by the Compagnie Française Thomson-Houston. The first commercial application was constructed and put in operation in 1950. Since then more than 100 broadcasting stations and more than 300 installations for industrial purposes, including rf heating, have been put into operation in Europe, Africa and America. Other European tube and equipment manufacturers have followed the lead of CFT-H and now almost all transmitters above 100 kilowatts output are being designed for vapor cooling of the modulator and power output stages.

The theory of operation has been discussed in several papers, as noted in Reference 1. Here we are interested in discussing the supplementary advantages vapor cooling can provide, which are:

- Hot water near the boiling point (95°C).
- Distilled water.

Space Heating and Distilled Water Production

By HELMUT LANGER, Development Engineer, The Machlett Laboratories, Inc.

accomplished utilizing the stored hot water from the daytime operation.

When heat recovery is desired, the vapor cooling installation requires a water cooled heat exchanger ahead of the air cooled heat exchanger, see Figure 2. It is furthermore necessary to provide a thermostat, which controls the water flow to the cooling circuit of the heat exchanger in order to obtain a constant water outlet temperature of approximately 95°C, independent of changes in the rate of plate dissipation of the power tubes. In a 100kW broadcast transmitter, with water entering the system at 20°C and leaving the heat exchanger at 95°C, about 180 gallons of hot water per hour will be obtained at no cost to the user. The heat obtained from the power tube is, therefore, about 800 Kilo Calories per kilowatt-hour. Reference 2, (Figure 3), describes hot water volume vs. anode dissipation for different output water temperatures in the secondary circuit.

If the available steam is not completely condensed in the water heater exchanger, then a portion will go to the air-heat exchanger; this heat is then dissipated in the air. It must be determined in each instance whether the heat exchanger should be convection or forced-air-cooled. Of course, when no heat recovery is needed, an air-heat exchanger only will be required and the heat dissipated may be released into the outside air.

Heat recovery and subsequent use for space heating and local hot water needs is certainly not limited to broadcasting installations, but will also be of value in the field of industrial rf-heating where high power levels are involved, e.g. induction melting of steel, tin re-flow, rayon drying, and many more. When planning a new installation using the vapor cooling process or changing to it from another cooling

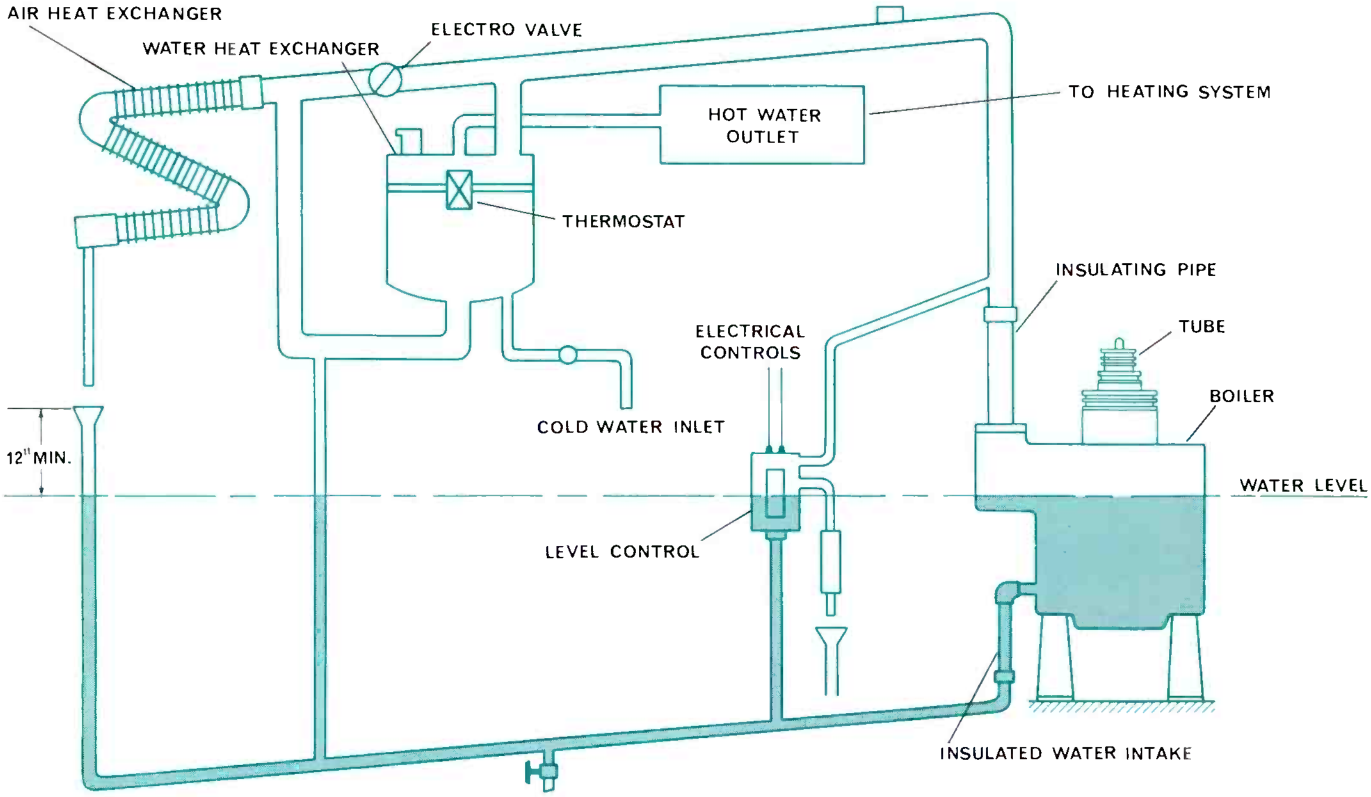


Figure 1 (below) — ML-7482 Vapor-Cooled Ceramic Triode. Note anode ribs or protrusions which promote efficient vaporization of water in boiler.

Figure 2 (above) — Diagram illustrates use of vapor cooling to provide hot water for heating of buildings and domestic purposes.

method, the advantages noted should be considered. It is certainly rather simple to utilize heat recovery and direct the available hot water into an existing heating system. If, for example, an oil-fired hot water system is used in the building, the oil-fired furnace may be treated as a supplementary device, only to be used when the vapor-cooled tubes are not in operation.

Production of Distilled Water

By tapping the outlet of a heat exchanger, a large fraction of the distilled water may be drawn off and utilized for industrial purposes. Compensation for water removal must then be made by feeding raw water into the vapor cooling boiler. A typical installation diagram is shown in Figure 4. The basic vapor cooling system remains unchanged; however, the boiler is equipped with an additional, insulated, raw water intake and a lower outlet for draining silt. Raw water has to be softened before it enters the boiler, and the raw water flow regulated in order to maintain a constant water level in the complete system. The distilled water may be stored in a water storage tank, (at time of removal from the heat exchanger the water will be very near the boiling point).

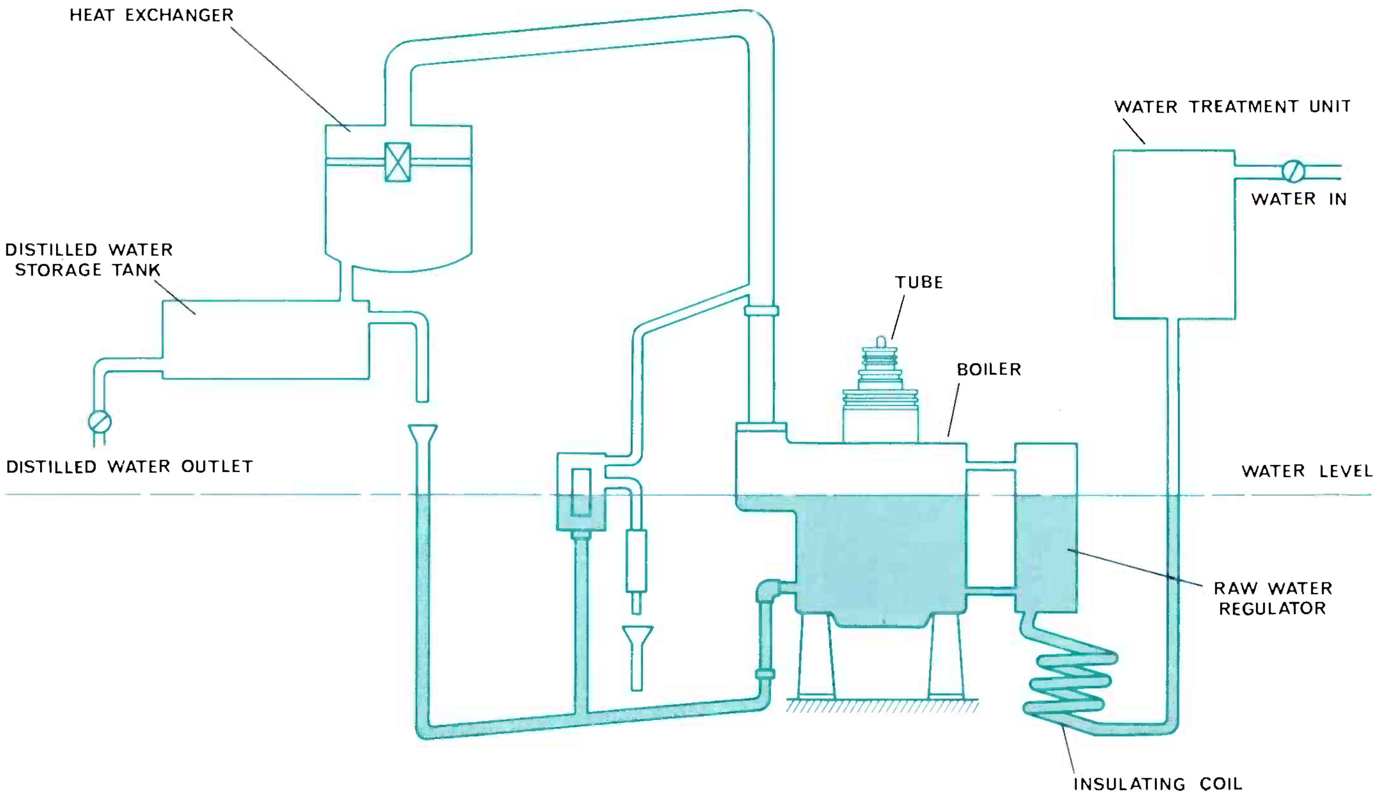


Figure 3 (above) — Diagram illustrates use of vapor cooling in production of distilled water.

Figure 4 (below) — Chart showing recovery of heat in form of hot water from Heat Exchanger.
($\Delta t = t_2 - t_1$ t_1 = incoming water temp.; t_2 = outgoing water temp.)

Production of distilled water can be regulated rather simply by use of a water level control in the storage tank, which would act to stop entry of distilled water into the tank when a certain water level is reached. An efficient, safely operating, distilled water supply system, and one which will not interrupt a basic vapor cooling system, may be readily designed by any competent heating engineer.

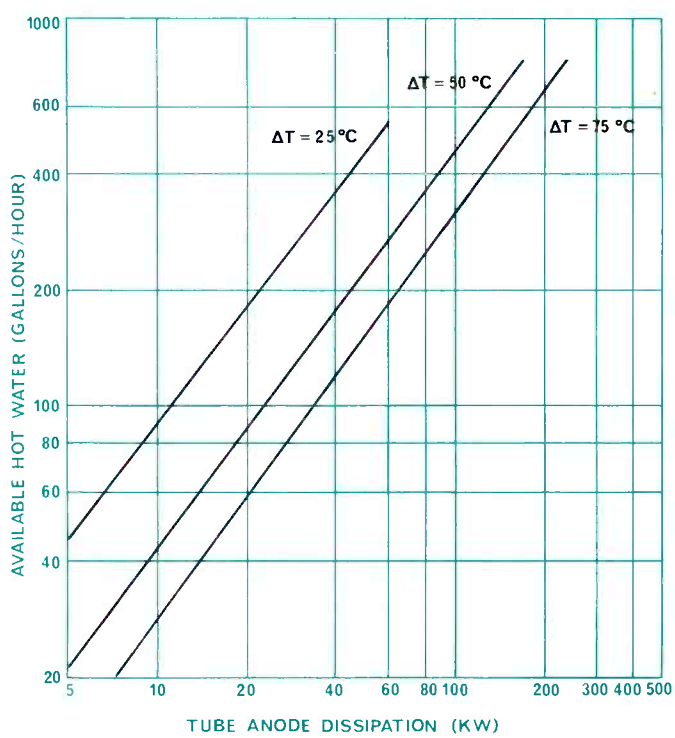
Conclusion

It has been shown that the vapor cooling process of large power tubes in broadcasting and in industrial heating application may, without much extra cost, supply hot water for heating and local uses and also make available large quantities of distilled water, which may be of advantage in certain industrial operations. (Several hundred liters of distilled water may be obtained daily from a tube of medium power output.)

REFERENCES

[1]"Vapor Cooling: Its First Major American Installation in the New 250kW Voice of America Transmitter." Cathode Press Volume 19, No. 1, 1962.

[2]"Note on the Vapotron" publication by the Compagnie Française Thomson-Houston, France.



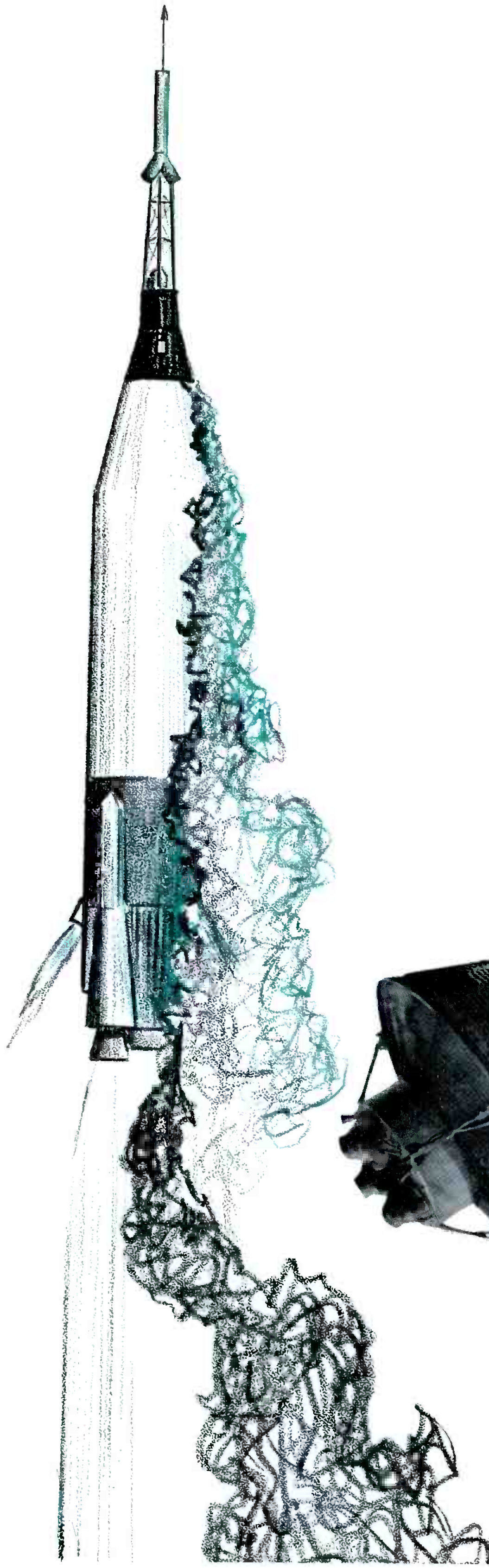
Editor's Note:

ACF radar beacons utilizing Machlett planar triodes have been incorporated in spacecraft used in the NASA Project Mercury. The ACF beacons, themselves, are part of a communications sub-system supplied by Collins Radio Company to the McDonnell Aircraft Corporation.

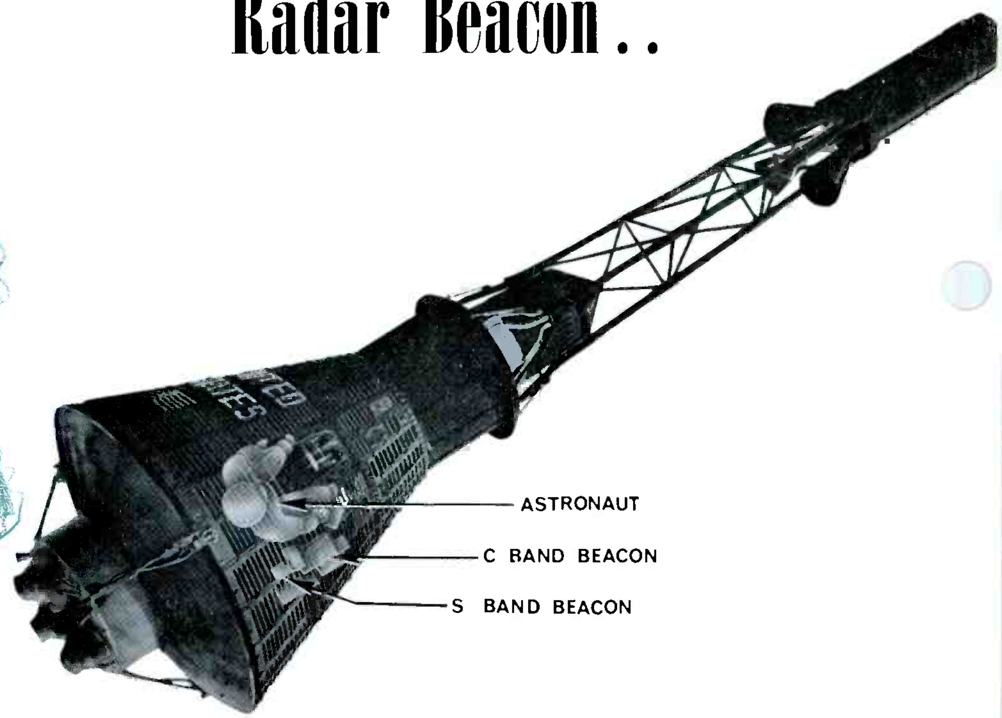
Machlett planar triodes, extensively used in radar beacon equipment used by commercial airlines and others, have been chosen for their long term reliability and for the excellent electron emission density provided by the tube's cathodes. A radar beacon is primarily a radar "responder" being actuated by a coded radar beam sending to ground units an identifying signal. These signals are monitored and tracked on the radar screen. It has been through the use of these beacons that the Mercury capsules have been tracked in orbit and pinpointed after descent.

Two beacons, for example, were aboard the Sigma 7 capsule.

Radar Beacon..



Mercury capsule employing ACF radar beacons in which Machlett planar triodes were used.



Mercury capsule showing location of radar beacons.

The First C-Band Pulsed 1kW Oscillator

Introduction

The recent marketing of a Radar Beacon, employing a C-Band pulsed 1 kW oscillator, by The ACF Electronics Division, Paramus, New Jersey, is of particular interest. For the first time a planar triode, ML-6771, has been used in this service and in this frequency range.

Planar Tube Experience in S-Band

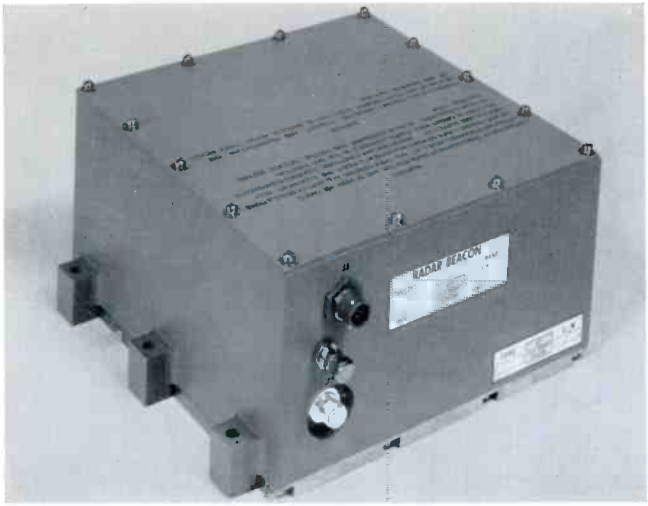
ACF Electronics Division, Paramus (one of three plants of the Division) is principally involved in production and development of light-weight equipment for aircraft, missile or submarine use for information, detection, transmission processing or display. As an important part of this activity, ACF has developed long-range radar beacons for missile and space application. These beacons provide pulsed output signals used for missile or space vehicle tracking, identification or pulse-coded signaling. Radar beacons must be light, fault-free in performance and capable of prolonged periods of operation in environmental extremes.

In their development and application of the Type 149-S S-Band beacon (1.5 kW pulsed power) ACF has employed the ML-471. Through the use of this tube, and because of reliable, long-life performance, ACF became interested in the possibility of using a Machlett triode as a magnetron replacement in their C-Band equipment, used in almost every major missile program.

Highest Reliability Required

Highly important space application, including the Mercury program, dictated the need for the utmost equipment reliability, especially with regard to transmitter and oscillator tube performance. By establishing special test criteria (developed in conjunction with Machlett engineering personnel) to match the tube to the cavity (Figure 3) it was found that the required performance standards could be obtained. Out of this arrangement the ML-471 was developed. Shock tests, to 100g for 5 milliseconds, have further demonstrated the ruggedness of the tube-cavity combination.

Of convincing interest was the long life experience provided by ML-471. Because of the excellent cathode emission, filament heater power was safely and satisfactorily reduced. An operating filament voltage of 5.9 $\pm$ .2 is now employed by the S-Band Radar Beacons (C-Band Beacons also use



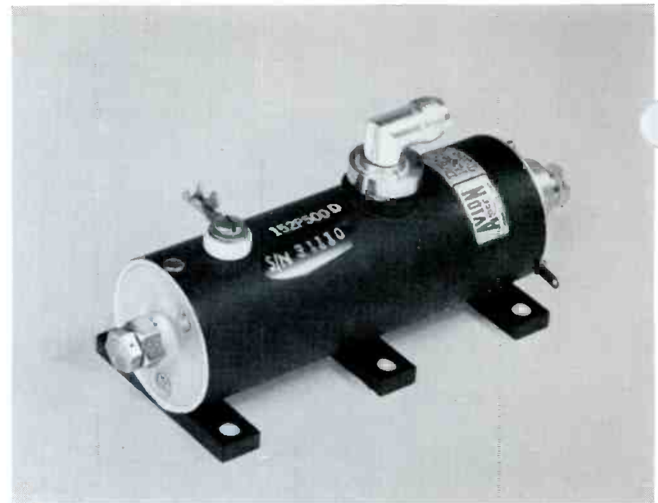


Figure 1 — Radar Beacon, Type 149, manufactured by ACF Electronics Division. This beacon used in S- (Type 149-S) or C-Band (Type 149-C) is employed in almost every major missile program. Transmitting tubes in all S-Band and some C-Band beacons are Machlett planar triodes.

Figure 3 — ACF Cavity, Model Number 331, S-Band Triode Pulsed Oscillator Cavity:

Frequency Range	2800 - 3000 mc
Peak Power Output	1.5 kw min.
Pulse Drive	2.4 kv @ 2.2 amps nominal
Filament	6.3 v @ 0.9 amps nominal
Duty	0.001 max.
Pulse Width	2 μsec max.
Size	Approx. 5½" Long, 1½" Dia. excluding connectors

Figure 2 — Machlett ML-471, planar triode, achieves life increase of 50%, or more, operating at an Ef of 5.9 ± .2 volts in Type 149-S Beacon employing the ACF Model 331 cavity. Excellent cathode activity permits pulsed power emission of 11 amps cm^2.

5.9 ± .2 volts). This filament voltage reduction has effected a life increase of approximately 50% or more.

Life/power tests performed at ACF and at Machlett have shown a consistent power level range (1.2 to 1.5 kW pulsed output) over the period of the test, 700 hours and 500 hours, respectively. In both instances the tube was operating satisfactorily at the conclusion of the test period. It is of interest to note that the ACF test was made with 6.3 v on the filament, the Machlett test with 6.0 v Ef, a comparison which provides good evidence of the tube's ability to operate under varied conditions: Field experience, over fifty flights in orbited satellites, has amply re-inforced test conclusions, and has conclusively demonstrated that the tube can perform well and long at lowered Ef.

Planar Triode in C-Band Beacons

The use of a planar triode in pulsed C-Band beacon equipment by ACF marks a positive advance in this field. Severe environmental conditions, associated with the use of the beacon, favor the use of planar triodes. There are, for

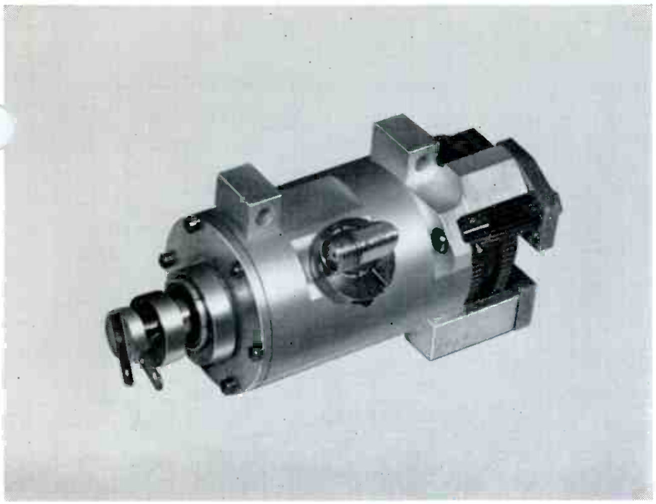


Figure 4 — ACF Cavity, Model Number 350, C-Band Triode Pulsed Oscillator Cavity:

Frequency	5400 - 5900 mc
Peak Power Output	1.0 kw (500 mc tuning range)
Duty Cycle	0.002 max.
Pulse Width	0.4 to 1.20 microsec.
Peak Anode Voltage	2.5 kv
Peak Anode Current	2.5 amp (nom.)
Vibration	10 g 20 - 2000 cps
Size	3¾" Long x 1½" Dia.

Figure 5 — Machlett ML-6771 — First Triode used in C-Band equipment. ML-6771 and its associated cavity, ACF Model 350, have successfully operated under tests to 30 g from 20 to 2000 cps.

example, no parts external to the tube which could be displaced to affect tuning. Further, the planar triode is less sensitive to voltage fluctuations and offers an economic advantage measured by a factor of four or more. Regarding comparison of sizes, the tube plus cavity is only a very slight amount larger than a magnetron of equivalent frequency range. All that was needed for the beacon was the right tube. Since the adoption of the ML-6771 by ACF for their C-Band Beacon, these desirable performance and economic parameters have been successfully incorporated in their equipments.

Employing a plate-pulsed oscillator, ACF's C-Band long range radar beacon is tunable throughout a 500 megacycle range from 5400 to 5900 mc. Nominal peak power of the transmitter is 1.5 kW (200 mc tuning range), available at a 0.001 duty, .4 to 1.0 μsec pulse width. (For lightness and compactness ancillary circuitry of the beacon is transistorized.) High reliability — in addition to that inherent in the tube — and sustained peak power performance is achieved by ACF by an exact mating of the tube to the cavity (Figure 4). Unusual structural reliability, for a tube of the 6771 type, is evidenced by the successful shock and vibration test, wherein the ML-6771 and its associated cavity, operated without detriment to performance at 30 g, from 20 to 2000 cps, on six different planes. The ability of the ML-6771 to operate under these conditions, hitherto prohibitively difficult, results from the tube's excellent mechanical structure and precise assembly as well as its high cathode activity and stability. Even under high voltage, high altitude conditions, the ML-6771 cathode (as well as that of the ML-471) shows no tendency to deposit cathode oxides on the grid assembly. Further evidence of cathode performance is found in the ability of the tube to operate at reduced Ef.

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Reliability under critical conditions is a mark of Machlett products. With the assignment of the ML-6771 and ML-471 to ACF radar beacon equipment, demonstration of this fact is once again provided.

Editor's Note:

Machlett planar triodes have been chosen for many exacting assignments in the nation's space programs. One of the most important of these has been the use of specially adapted ML-6771 tubes in Mariner II, the Venus spaceprobe. These were the only electron tubes in the Mariner rf circuitry. Other interesting space usage of Machlett planar triodes is described elsewhere in this issue in an article on ACF radar beacons.

In the S-Band transmitters of the Nimbus weather satellite a frequency stable triode, ML-518 is employed for use during the brief transmission periods made by the satellite. The fact that the ML-518 can be brought to frequency stable operation within an extremely short period of time eliminates the need for long warm-up periods and thereby reduces power consumption requirements. Nimbus will transmit fourteen times each twenty-four hours as it passes near Fairbanks, Alaska on its near polar orbit; only ten of these transmissions, however, will be within the range of the Fairbanks' ground station. A satellite design life of six months, minimum, is expected. During this period over two hundred and thirty thousand photographs of the earth's surface (including, of course, its cloud cover) will have been transmitted to Fairbanks.

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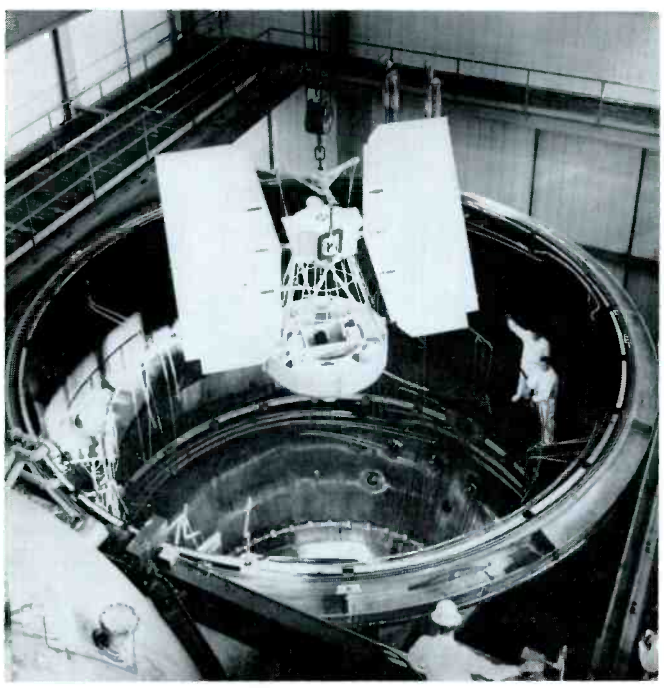
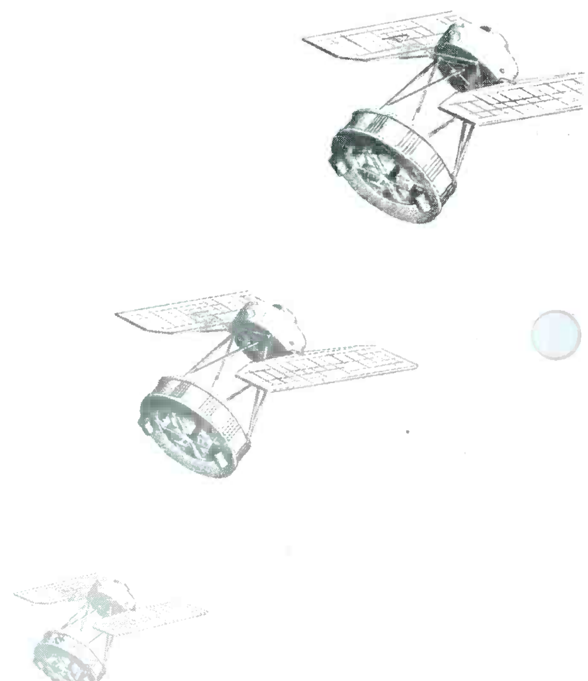
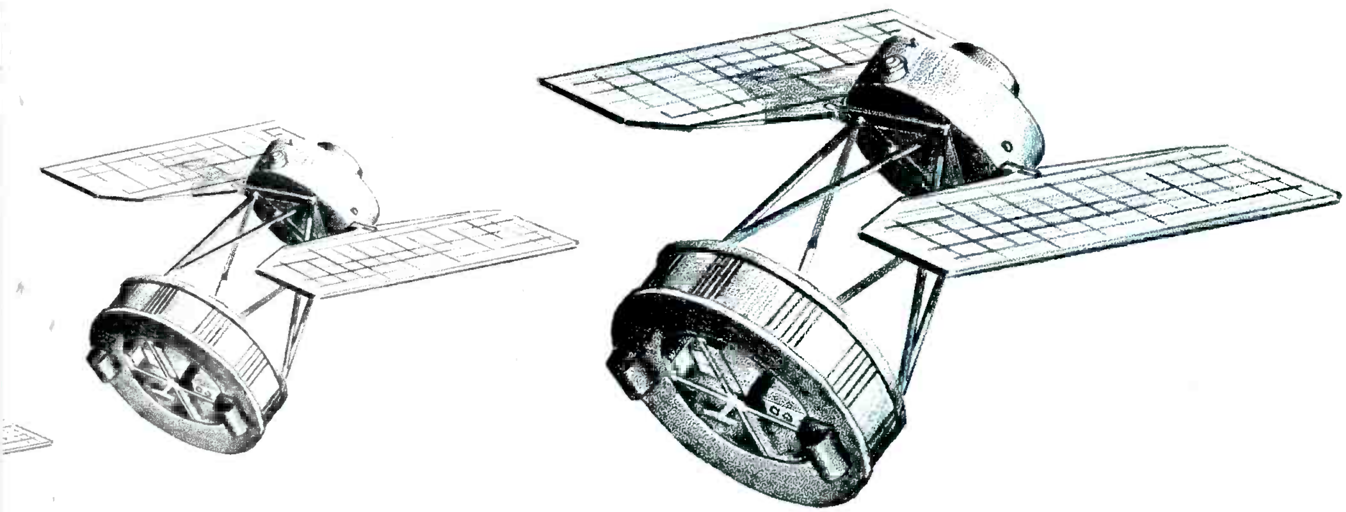


(Photograph courtesy of General Electric Company)



As the accompanying photograph (taken at General Electric's Missile and Space Division, Valley Forge Space Technology Center) indicates, Nimbus will have undergone extensive testing before it is sent aloft. Nimbus is shown here entering MSD's Environment Simulation Chamber.



Nimbus Weather Satellite

Introduction

A meteorological satellite, Nimbus, scheduled for operation in late 1963, is being developed by the Goddard Space Flight Center of NASA. General Electric Co. is fabricating the spacecraft structure and will integrate the various subsystems produced by other manufacturers. Telemetry Transmitters, employing the ML-518 frequency stable planar triode, have been provided for Nimbus by General Electronic Laboratories.

Stringent transmission requirements include a 45 second warm-up period* for the transmitter followed by a ten minute transmission. The Machlett triode, ML-518** specifically designed for fast stabilization meets this difficult operating condition satisfactorily.

*Cathode temperature stabilization for the planar triodes is reached prior to this period.

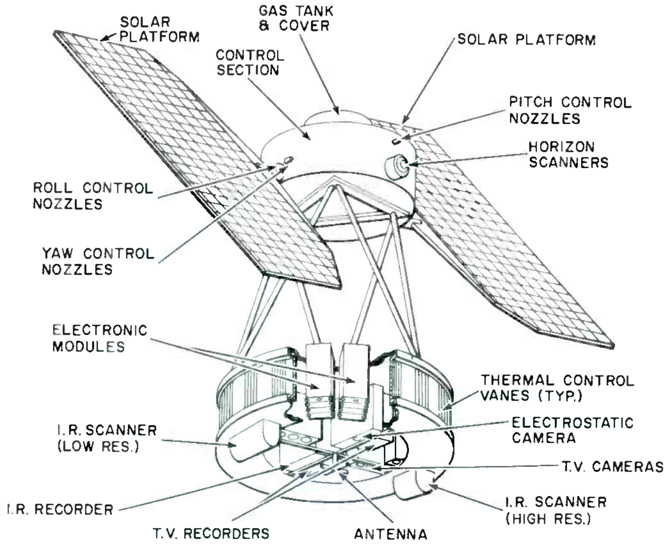
**Frequency Stable Anode Design for Planar UHF Tubes, by Werner Brunhart, Cathode Press, Volume 18, Number 3.

General

Nimbus is designed primarily to maintain a continuous watch, by vidicon cameras, of the earth's daytime cloud cover. (Clouds are, of course, basic weather indicators.) The satellite will follow a nearly circular orbit at an altitude of 600 miles. It will be stabilized about each axis and kept in a perpendicular orientation to the earth's surface. A site in Alaska will acquire and store monitored data from the satellite and will also inject certain command functions.

The Satellite

The Nimbus Spacecraft consists of control and information sections rigidly interconnected (see Figure 1). In operation the control section, electrically powered by solar cells, utilizes inputs from infrared scanners to establish horizon references and thus the desired orientation of the craft. Compressed nitrogen jets and flywheels act to stabilize



(Diagram courtesy of the General Electric Company)

Figure 1 — Nimbus Spacecraft showing major sub-systems and components. S-Band telemetry transmitters designed and manufactured by the General Electronics Laboratories are located in the lower section of the structure.

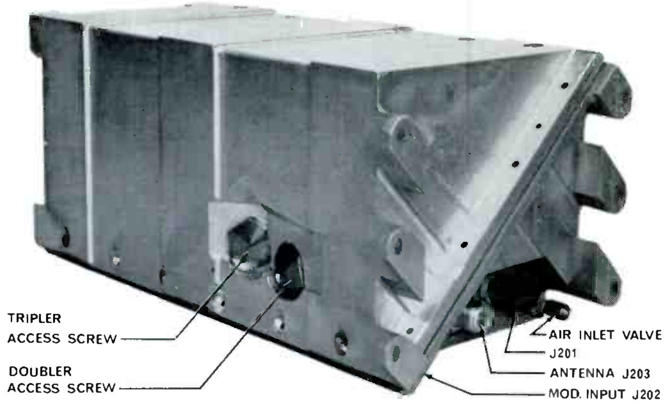


Figure 2 — The S-Band Telemetry Housing employs cast magnesium fabricated in two sections. The total weight of the transmitter is approximately 19 pounds.

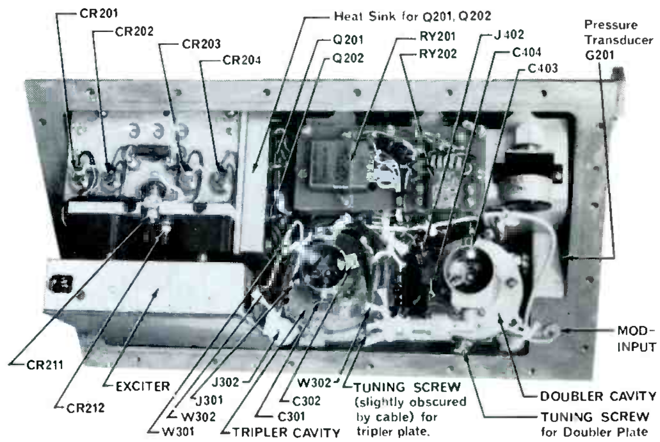


Figure 3 — Block diagram of Model 25A1 S-Band Transmitter.

the unit and provide corrective forces from signals generated by the scanners through a small space-borne computer. Solar paddle/sun orientation is derived from a sun-sensor; yaw gyro drift is also monitored from the sun system.

The information or sensory system of the satellite consists of over 16 different sub-systems including:

(1) S-Band 5 watt Transmitters having a frequency stability of .005%. (FM transmitters employ ML-518s in 1700 mc band to transmit to the ground station information from the Advanced Vidicon Sub-system and the high resolution radiometer sub-system.)

(2) Advanced Vidicon Sub-system (To take cloud cover pictures; employs 3 cameras, one normal to the earth's surface, the others displaced to provide a slight picture overlap; pictures from cameras are stored on 4-track tape recorder; upon command from ground station vidicon information is transmitted on S-Band.)

(3) High Resolution Radiometer Sub-system (To provide nighttime cloud cover picture; utilizes infrared radiation in the 3.4 to 4.2 micron region.)

Other sub-systems include those for telemetry and for measuring infrared radiation from certain spectral bands and earth-sun experiments to determine the role of the sun in earth's weather.

S-Band Telemetry Transmitter

The telemetry transmitter used in Nimbus is a self-contained unit (two are employed to provide the highest reliability practical) designed to operate in the 1700-1850 mc/sec region. Designed primarily for use with FM sub-carrier or sinusoidal wide-band video, the transmitter, General Electronics Model 25A1, can with minor modification transmit asymmetrical data of the PCM or PACM (Pulse Amplitude Code Modulated) type.

Designed for lightness and reliability, the unit is packaged in a cast magnesium two part housing (Figure 2 and 2A), and employs epoxy encapsulated miniature vacuum tube circuit sections and magnesium cavity castings for the final tube sections. A complete unit weighs approximately 19 pounds.

A block diagram showing the major sub-portions of the 25A1 transmitter is given in Figure 3. The basic unit consists of a modulated oscillator, stabilizing circuitry, multiplier chain and output stage as well as a power supply together with auxiliary circuitry for monitoring transmitter performance. Since ruggedness and frequency stability have

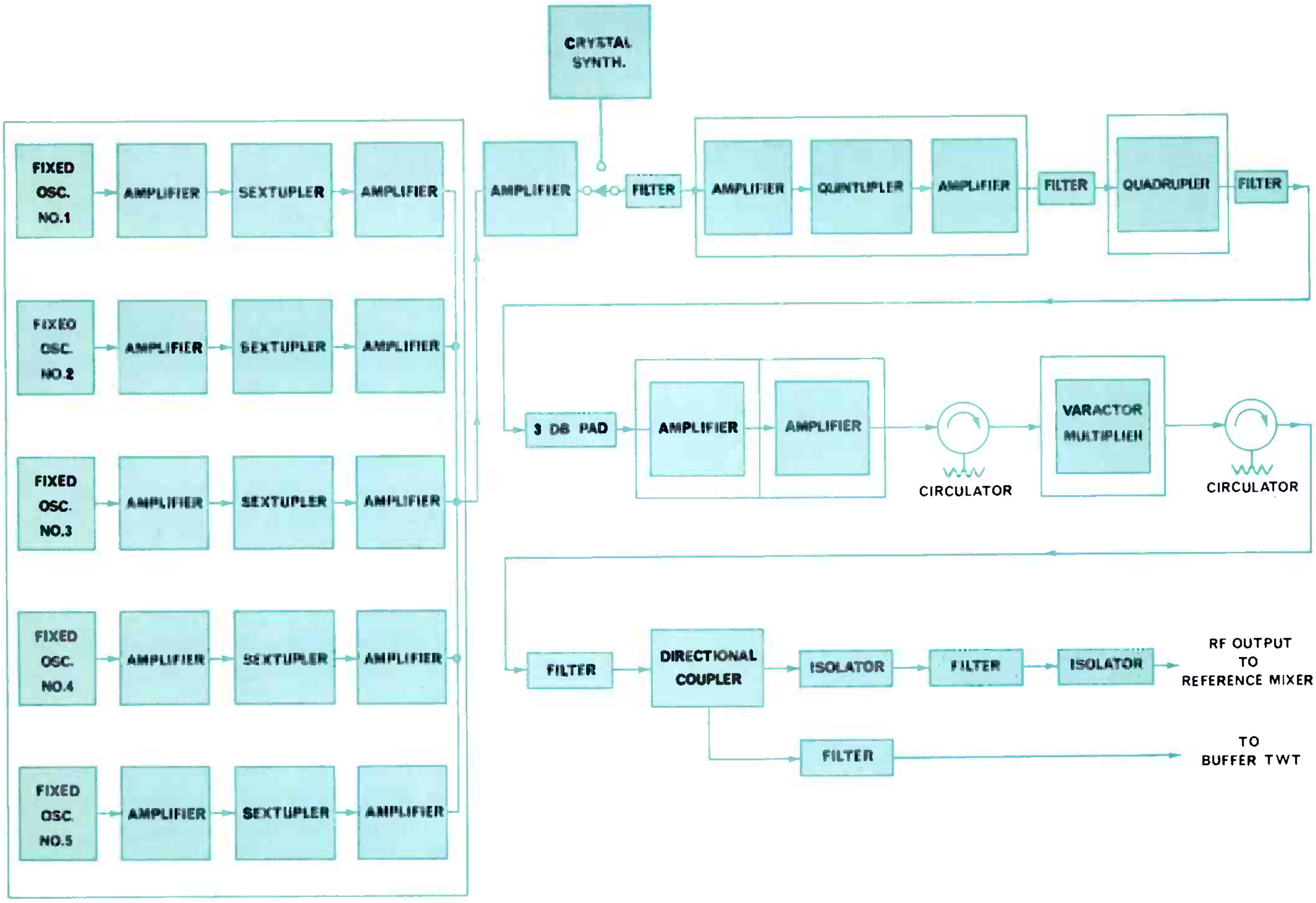


Figure 2A — Model 25A1 S-Band Transmitter.

been critically important in the transmitter design, both circuit configurations and components have been selected with this criteria in mind. The oscillator, for example, uses a Clapp circuit to achieve a minimum of incident frequency modulation (such as might result from external vibration). To further enhance stability, portions of the oscillator are secured to the chassis by epoxy adhesives. A crystal discriminator determines the average frequency of the oscillator, the average center frequency deviating only slightly (less than .005%) from the desired center frequency over 60°C range.

Following this two doubler stages work into a final amplifier stage which, in turn, works into a tripler and a doubler, each employing the ML-518. Operating in a grounded-grid mode the tripler stage utilizes a radial cavity (Figure 4) with capacity loading to minimize volume. The cavity operates at a one quarter wavelength anode; tuning

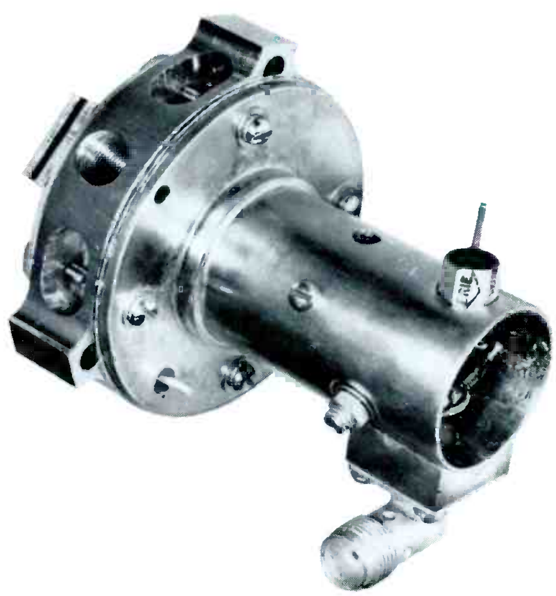


Figure 4 — Radial cavity employed in tripler stage which uses ML-518.

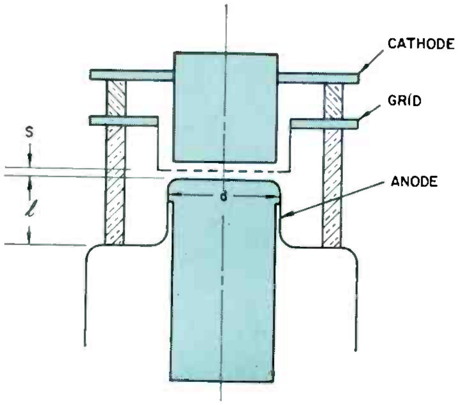


Figure 5 — Typical Planar Tube Design of 2C39WA Construction.

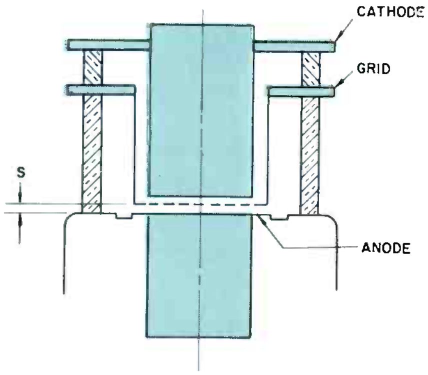


Figure 5A — Planar Tube with Frequency Stable Anode Design as in ML-518 and ML-7855.

Figure 6 — ML-518.

screws vary cavity resonance by variation of end loading capacity. Power transfer from the tripler to the doubler cavity is effected by tapping the plate line at a maximum point.

The final or doubler stage is similar, in characteristics, to the tripler stage. The output, of approximately 6.0 watts, is coupled to the load by means of a loop.

ML-518

The ML-518 is a UHF planar triode employing a frequency stable anode, and high alumina ceramic insulation. Designed to operate as an oscillator, amplifier and frequency multiplier, the tube has a maximum frequency rating of 2500 Mc. Smaller in overall height than the typical Machlett planar triode, the ML-518, which has a maximum plate voltage of 600 v, provides a dimension "A" (bottom of cathode connection to top of anode) of a maximum of 1.507 inches; this compares to dimension "A" of the ML-7855 of 1.815 inches, and which has a maximum plate voltage of 1000 volts.

The frequency stable anode effectively eliminates the drift problems associated with conventionally designed tubes used intermittently or required to perform after a 45 seconds warm-up time following cathode temperature stabilization. In the typical planar triode the initial thermal changes effect a difference in grid-anode capacitance. This, in turn, creates a frequency shift, the initial magnitude of which may run into tens of megacycles. With the frequency stable tube, such as the ML-518, frequency drift is small, initially, tens of kilocycles, and stability is achieved within a few seconds. Conventionally, frequency stability does not occur until several minutes — perhaps 15 or more — after application of plate voltage.

In Figure 6 a schematic view is shown of the typical re-entrant anode design. Factors causing anode expansion, hence those that affect frequency shift, are the re-entrant distance of the anode, its material and the temperature change from the initial condition. Re-design of the anode structure, schematically shown in Figure 6, results in a structure whose anode is almost unaffected by thermal changes.*

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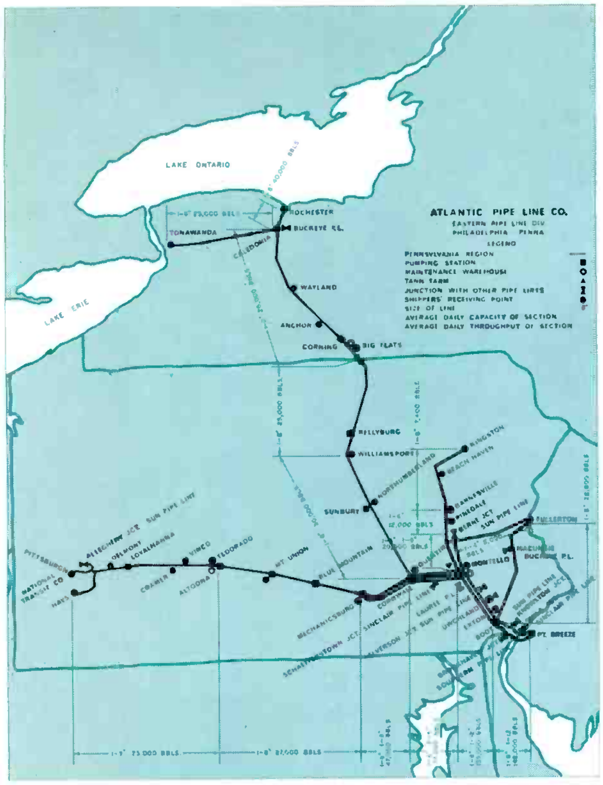
The Machlett Laboratories' strong position in specialized electron tube offerings is well exemplified by its UHF planar triode group. Planar types for pulsed service, quick warm-up, high cathode current, or for frequency stability, are now established catalog items. In outer space, or in the inner air space — wherever communications requirements are the most stringent and the design problems most exacting — Machlett planar triodes will be found in operation.

*Both the ML-518 and ML-7855 (operates at higher plate powers) provide stability of operation in telemetry circuits or where voltage fluctuation is a possibility, because of the use of light unregulated supplies. For example, in pulse coded use differing duty cycles will affect the power dissipated by the anode, hence the anode temperature. The frequency stable tube will not be significantly affected by such changes.



Atlantic Pipeline Company:

Microwave User Since 1949

Introduction

Pipeline and other right-of-way companies, confronted with the complex problems of scheduling, precise timing and transmission of varieties of essential data, turned early to the use of private microwave communications. Utilizing circuits and components first developed during the early '40's various equipment manufacturers had readied reliable microwave units by 1948-1949. In 1949 the first privately owned microwave system was installed by the Keystone Pipe Line (now the Atlantic Pipe Line) in five stations between Philadelphia and Reading, Pennsylvania. Soon thereafter, other pipelines became enthusiastic pioneers in this new field of electronics. Continuous growth since this time has seen the installation of nearly 30,000 miles of microwave network by over 100 individual companies.

Utilizing a two thousand megacycle system, Atlantic Pipe Line has generated hundreds of thousands of hours of tube life in a communications system which has grown to 25 stations since 1949. In doing so it has not only developed highly systematized and useful maintenance techniques, but has achieved significant performance criteria through the many records it has kept. Planar triodes are employed in Atlantic Pipe Line's microwave rf equipment as frequency multiplier, transmitter final output and as receiver local oscillator tubes. Of the types used, two manufactured by The Machlett Laboratories — ML-2C39A and ML-3CX100A5 — have seen extensive service. Typical field tube life, as will be noted in more detail below, approximates two years or nearly 16,000 hours.

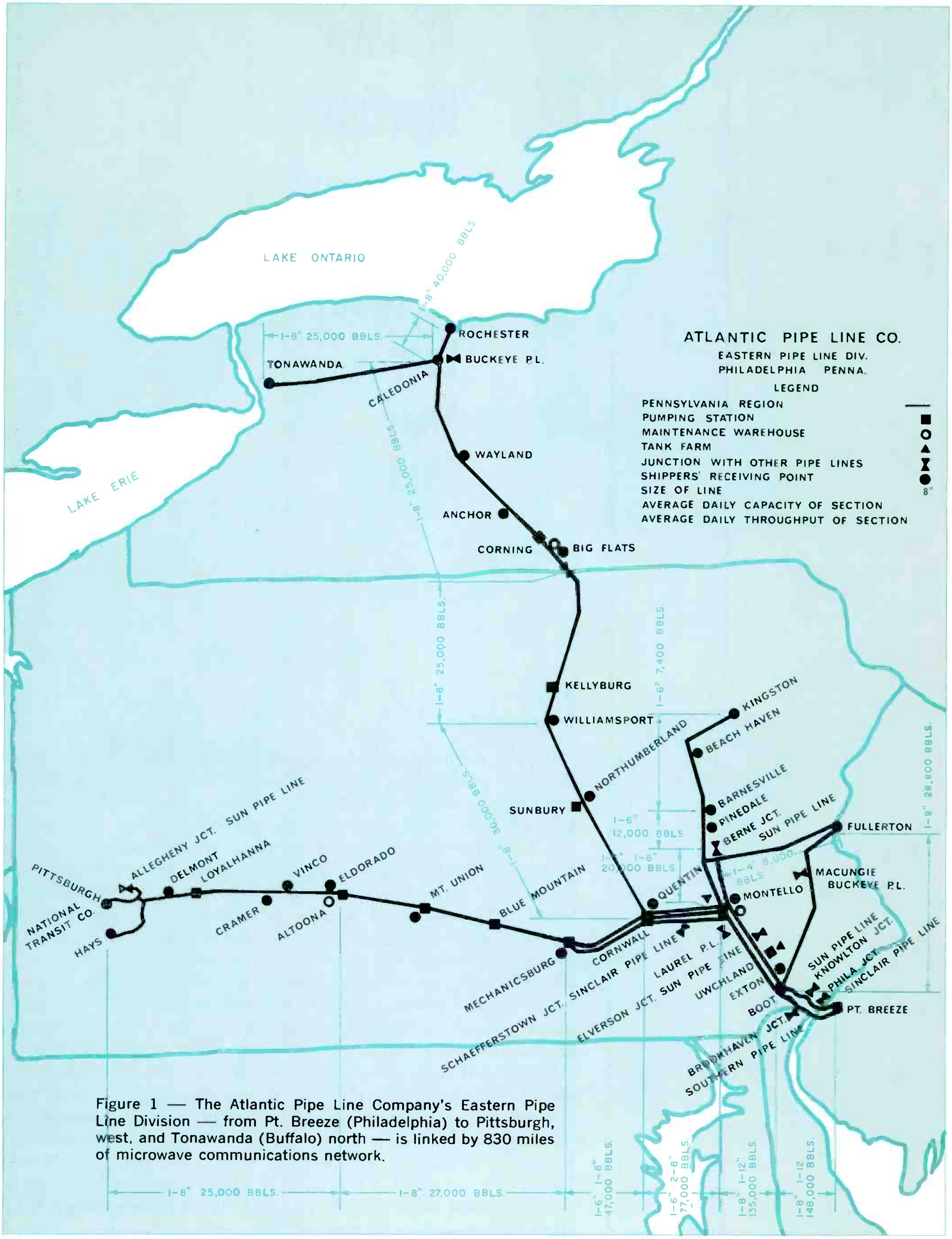


Figure 1 — The Atlantic Pipe Line Company's Eastern Pipe Line Division — from Pt. Breeze (Philadelphia) to Pittsburgh, west, and Tonawanda (Buffalo) north — is linked by 830 miles of microwave communications network.

Figure 2 — The S. S. Atlantic Challenger, on its maiden voyage from Venezuela, in 1962, passes under the Walt Whitman Bridge in Philadelphia. 743 feet long, 105 feet in breadth, this huge tanker can bring a maximum of over a million tankfuls of gasoline to the Company's eastern terminus.

S. S. ATLANTIC CHALLENGER
(the newest and largest Atlantic Refining Co. tanker)
Length Over All, 743 feet; Breadth, 105 feet; Deadweight, 48,000 tons; Maximum Cargo Tank Capacity, 413,000 barrels (42 gallons per barrel); and Speed, 17.5 knots per hour.

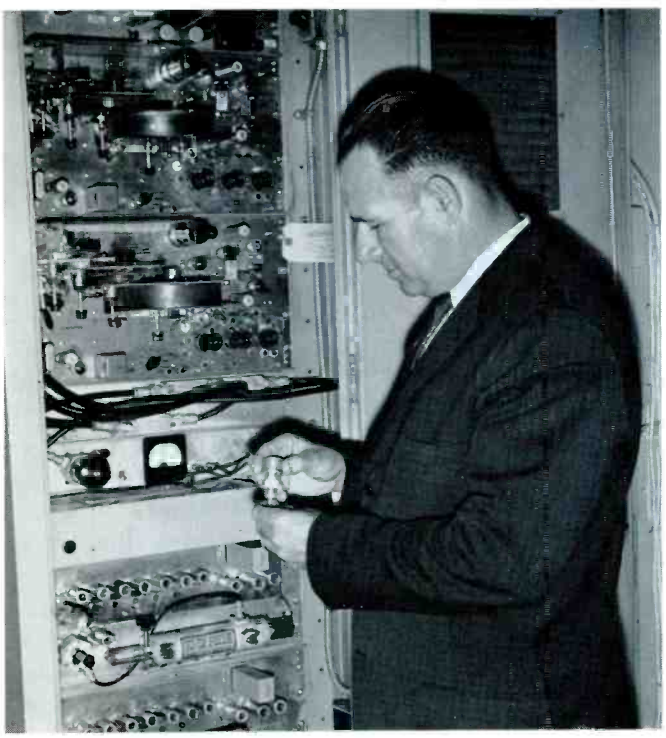


Figure 3 — Mr. L. R. Yoder, Communications Supervisor, inspects an ML-7289/3CX100A5 at the Company's Broad Street (Philadelphia) microwave station.

A Pipe Line System: Continuous Performance

The Eastern Division of the Atlantic Pipe Line Company has a potential throughput of 5,500,000 gallons of petroleum distillates daily. Taking its supply from nearby refineries and marine tanker terminals the Point Breeze Pump Station in Philadelphia receives petroleum products destined for Scranton, Pittsburgh, Buffalo and Rochester, as well as intermediate points and interconnecting pipelines to Cleveland, Ohio and Syracuse, N. Y. Strategically placed pumping stations, operating at pressures up to 1200 lbs. per square inch, move refined oils, gasoline and butane over the Appalachian ridges of central and northern Pennsylvania and up into Western New York State. The daily variety of fluids in the line normally consists of furnace oil, kerosene and various grades of gasoline from a number of shippers. A typical day in the Eastern Division will find as many as 20 separate batches of different products in the line, and an average of 30 deliveries to the 63 delivery points along the system.

To avoid the unhappy result of providing a shipper with several thousand gallons of fuel oil when his needs called for high test gasoline — and even more, to provide the shipper with all the furnace oil he needs when, for example, sudden heating demands require it — calls for painstaking plotting of demand curves on hourly schedule charts of wall sized magnitude. Operating on a three week lead time, deliveries are scheduled to the five minute period.

Figure 4 — Pumping station at Caledonia, New York, at the junction in the line between Tonawanda and Rochester.

Communications: Reliability, Flexibility On Demand

A pipeline requires a variety of communications circuits to meet its daily needs. Point-to-point voice circuits for dispatching and administrative use, remote control of mobile radio base stations, telemetering and remote control of unattended pump stations, alarm and signal systems all go to make up the complex of communications. Rapid pipeline response under critical conditions requires not only rapid communications (as nearly instantaneous as possible) but also the highest order of reliability.

The typical Atlantic PTM microwave equipment provides up to 45 audio channels of 3.5 Kc each. Each voice signal modulates the time of occurrence of a video pulse. These pulses, in turn, amplitude modulate a 1900 Mc transmitter having output rf power of up to forty-five watts peak. Without the continued, effective functioning of these microwave units, Atlantic Pipe Line could not, except with extreme difficulty, operate properly. Reliable communications require a continuous maintenance surveillance — preventive medicine, so to speak — to keep the system in top operating condition.

Atlantic must keep in peak operating trim 25 microwave transmitting-receiving stations located at 20 to 50 mile intervals. All are unattended. All of them, of course, require towers (up to 200 feet) and feed lines of varied length. Almost all have standby generators for power fault conditions. System maintenance, including the maintenance of associated tone, control, telemetering, telephone units, etc., is obviously no simple task. It requires its own precise schedul-

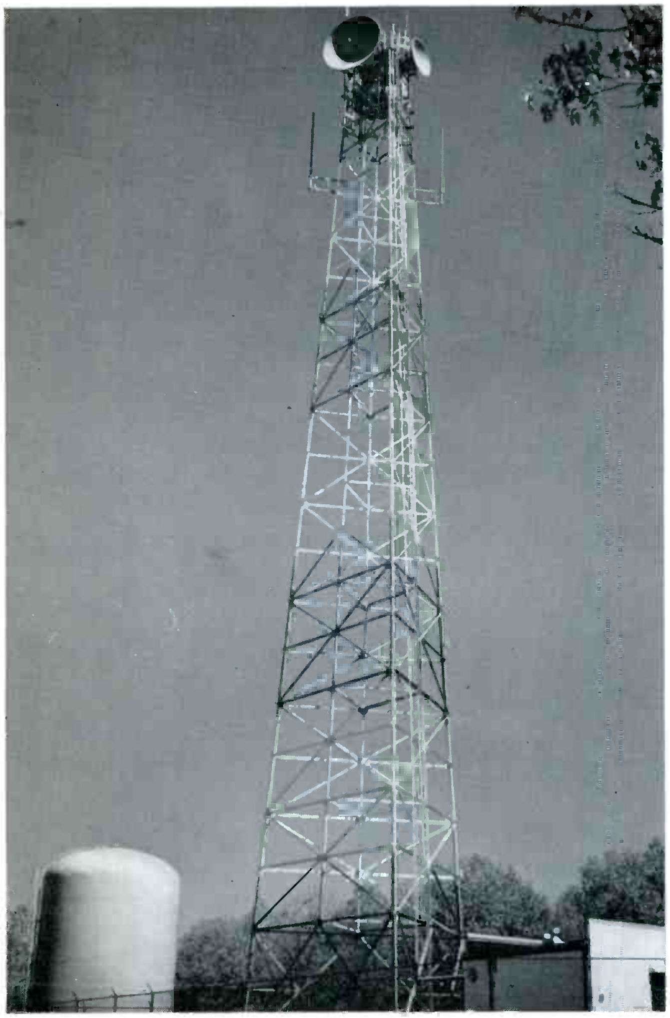


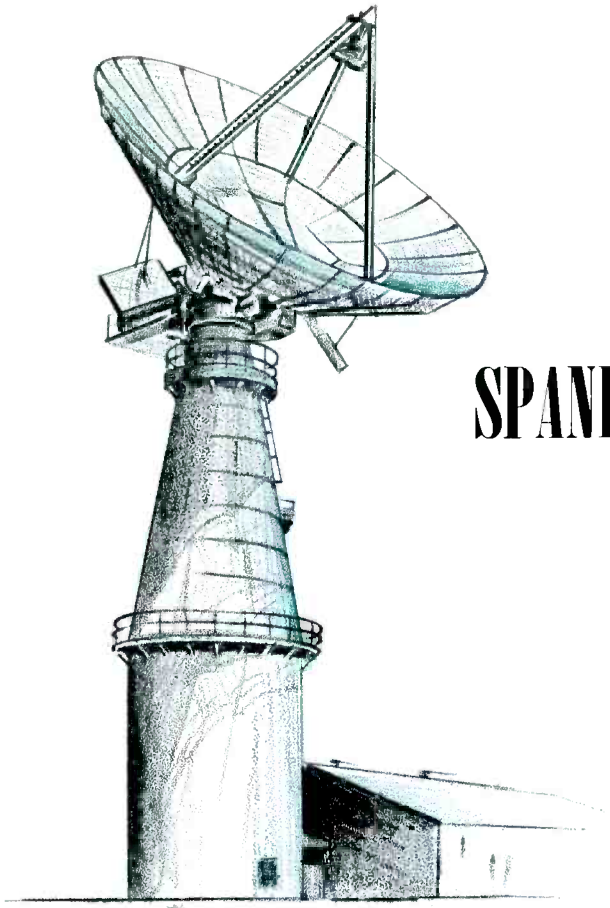
Figure 5 — Valley Forge Microwave Station, unattended operation here is typical of the Company's many installations.

Figure 6 — ML-7289/3CX100A5.

ing and planning. Basic to the maintenance program is the prevention of system outages by the elimination of tube difficulties. Three important factors are operative here: (1) The "pre-signalling" provided by the microwave rf planar triode (2) The extensive records and tube history kept by Atlantic (3) The purchase of the most reliable available electron tubes.

The typical planar tube complement in Atlantic's microwave transmitters consists of three tubes in a multiplier chain (450 Mc, 960 Mc and 1900 Mc) and a final tube at carrier frequency. A planar tube is also used as a local oscillator in the receiver. Since cathode heating power is the single most important factor in planar tube operation, insofar as long life is concerned, precise attention was paid to this matter by the equipment designer, ITT Kellogg. At the low end and middle of the multiplier chain 5.5v is maintained at the heater terminal; at the high end 5.3v is maintained. Since thermal stability is also of great importance in the maintenance of long tube life, heater power is never shut off except for emergency repairs. Under these conditions, Atlantic finds that the ML-2C39A, used in the first two stages, averages 16,000 hours and the ML-3CX-100A5, used in the higher frequency stages, averages 13,000 hours.

Individual planar tube replacement is kept at an economical minimum, commensurate with the needs of reliability by observing the gradual change of cathode current level. Monthly monitoring of tubes provides this data as well as other information. Tube breakage is almost nil. Field spares are one tube for each four in service.



SPANDAR: NASA's Long Range Tracking

By JAMES S. WALSH, Senior Engineer,
Equipment Division,
Raytheon Company

JAMES S. WALSH

James S. Walsh joined the Raytheon Company in 1956 and has, since then, been active in the field of radar transmitters. Now a Group Leader (Transmitter Section, Range Instrumentation and Surveillance Dept., Surface Radar and Navigation Operation, Equipment Division) Mr. Walsh has had a comprehensive experience which includes work with: hard-tube and hydrogen-thyratron circuits and components; high-stability pulsed coherent amplifier chain transmitters; magnetron, amplitron, klystron, triodes, tetrodes and travelling wave tubes; and instrumentation for measuring time and phase stability of high stability mti radar transmitters. Mr. Walsh, who received his A.E.E. degree from Northeastern University, was the project enginer on the NASA Spandar Transmitter.

Introduction

SPANDAR is the National Aeronautics and Space Administration's long range tracking radar at Wallops Station, Wallops Island, Virginia. The SPANDAR radar system is a successful integration of system components designed by various equipment manufacturers and assembled (with some equipment modifications) by NASA and Lincoln Laboratory engineers and scientists. The antenna, pedestal and tower are similar to those employed in Lincoln Laboratory's Millstone Hill radar; the range unit is a modified Reeves-Verlot unit; the transmitter was designed, constructed, and installed by the Raytheon Company to NASA specifications, written specifically for the SPANDAR system.

Long range tracking of rockets is accomplished primarily by three means; the conventional skin tracking in which tracking is accomplished by employing the return of a signal reflected from the surface of the vehicle transmitted by the ground based radar; beacon tracking in which tracking is accomplished by employing a signal emitted from a rocket-borne transponder, when the transponder is interrogated by a ground based radar; and telemetering tracking in which tracking is accomplished by employing a telemetering signal emitted from equipment borne by the missile. A ground based radar transmitter is not required for the last of these techniques.

The three techniques mentioned each have their advantages and disadvantages and are usually employed to complement one another. The primary advantage of skin tracking is its independence of rocket borne equipment, and the fact, therefore, that it can provide tracking in the event of rocket borne equipment failure.

Radar Transmitter — Its Design and Performance

Figure 1 — NASA's SPANDAR, long range tracking radar, at Wallops Island, Virginia, employs a Raytheon designed, constructed and installed radar transmitter using the ML-7560 as a modulator switch tube. Shown here are the 60-foot parabolic antenna and 90-foot tower of the installation.

Design and Performance Features of SPANDAR

The primary role of SPANDAR, a skin tracking radar, is the long range tracking of rockets or other space vehicles. The system is also equipped with instrumentation for beacon tracking. The antenna system includes a 60-foot diameter parabolic dish mounted on a 90-foot tower. (Figure 1). Acquisition is accomplished either from data supplied by a manually operated optical tracker, or by data supplied from other smaller, shorter range radars.

The performance of the integrated SPANDAR system has been outstanding. SPANDAR has provided skin tracking ranges of approximately three times other Wallops Island radars. Figure 2 is a plot of the track of a JAVELIN vehicle launched from Wallops Island. SPANDAR has tracked the fourth stage of a SCOUT rocket launched from Wallops Island for over 1,000 nautical miles. SPANDAR also tracked the Echo II balloon launched from Cape Canaveral to horizon impact.

The SPANDAR transmitter produces five megawatts of peak power and ten kilowatts of average power at S-Band over the frequency range of 2700 to 2900 Mc. Some of the more salient transmitter features are:

A. Broad-Banded — needs no tuning over the frequency range of 2700 to 2900 Mc.

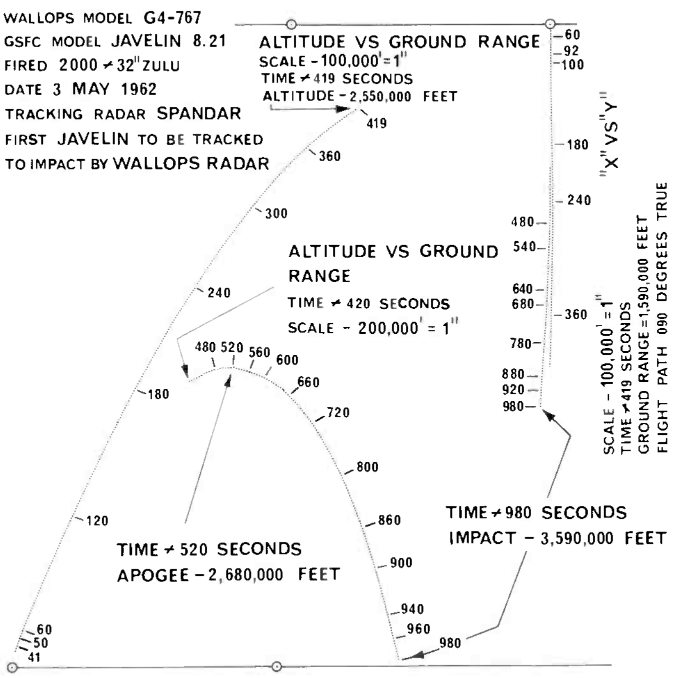


Figure 2 — Plot of a track, made by SPANDAR, of the JAVELIN vehicle.

B. High Frequency Stability — 1 part in 10^9 short term, 1 part in 10^6 long term.

C. Continuously Adjustable Output Power — from full output to —40 db.

D. Continuously Adjustable Output Frequency — from 2700 to 2900 Mc in 100 kc steps.

E. High Output Frequency Precision — Five (5) fixed transmitter frequencies are provided to a precision of one part in 10^7.

F. High Phase Stability — The pulse-to-pulse transmitter phase stability is 0.5 degrees peak-to-peak maximum.

G. Fast Rise and Fall Times — The rf output pulse rise and fall times are 50 and 100 nanoseconds respectively.

H. Pulse Coding — The transmitter can produce three one-μsec pulses, two two-μsec pulses or one five-μsec pulse. The time between pulses can be continuously varied between six and forty microseconds or time-tone modulated for beacon tracking purposes.

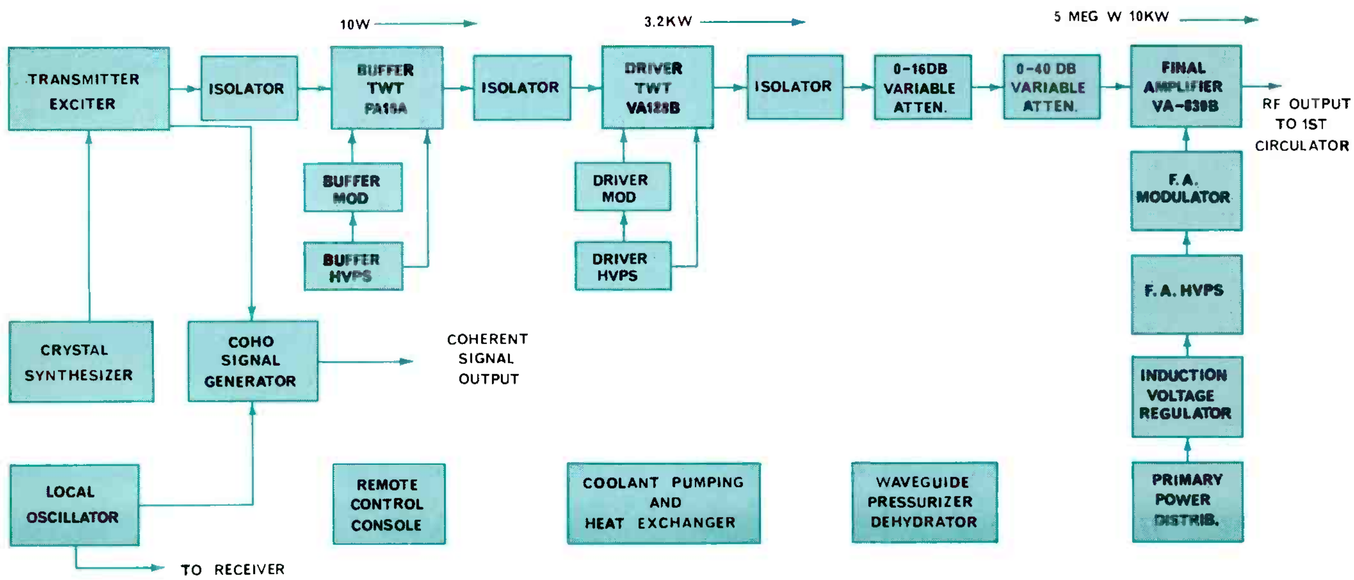
I. Pulse Repetition Frequency — 200 to 400 pps.

J. Power Programming — The transmitter output power can be programmed to vary inversely as the square of the target range from full output power at a target range of 200,000 yards, to —40 db at zero target range to provide protection for "on-board" receiving equipment.

K. Remote Control — A remote control console is provided for complete transmitter remote control and monitoring.

L. Local Oscillator — The transmitter is provided with a highly stable local oscillator at a frequency 30 Mc

Figure 3 — Block diagram of SPANDAR Transmitter.



removed from the transmitter frequency for receiver use.

M. Coherent Output Signal — The transmitter provides a highly stable coherent output signal at 30 Mc for all transmitter frequencies.

Figure 3 is a block diagram of the SPANDAR transmitter. As shown in the block diagram, the transmitter is a Master Oscillator-Power Amplifier type system employing three power amplifier stages in cascade. Pulse shaping and power programming are performed in the driver amplifier stage.

Details of the microwave system following the output of the final amplifier have been omitted and will be described separately.

Transmitter Design Details

Final Amplifier Stage

The final amplifier stage employs a Varian Associates VA-839B klystron as the microwave power amplifier pulsed by a hard tube modulator through a pulse transformer. The modulator pulse is designed to overlap in time the rf drive pulse for all transmitter pulse widths, thereby causing the output rf pulse waveform to be determined by the rf driving pulse rather than the modulator video pulse. This technique simplifies the design of final amplifier modulator at the expense, of course, of final stage efficiency. The klystron operates at a peak voltage of 140 kv at 104 amperes. The

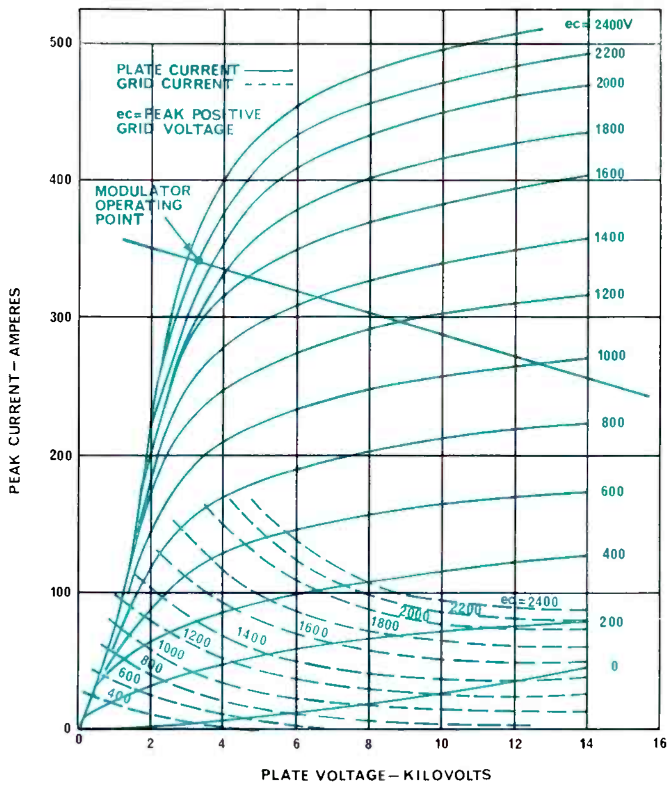
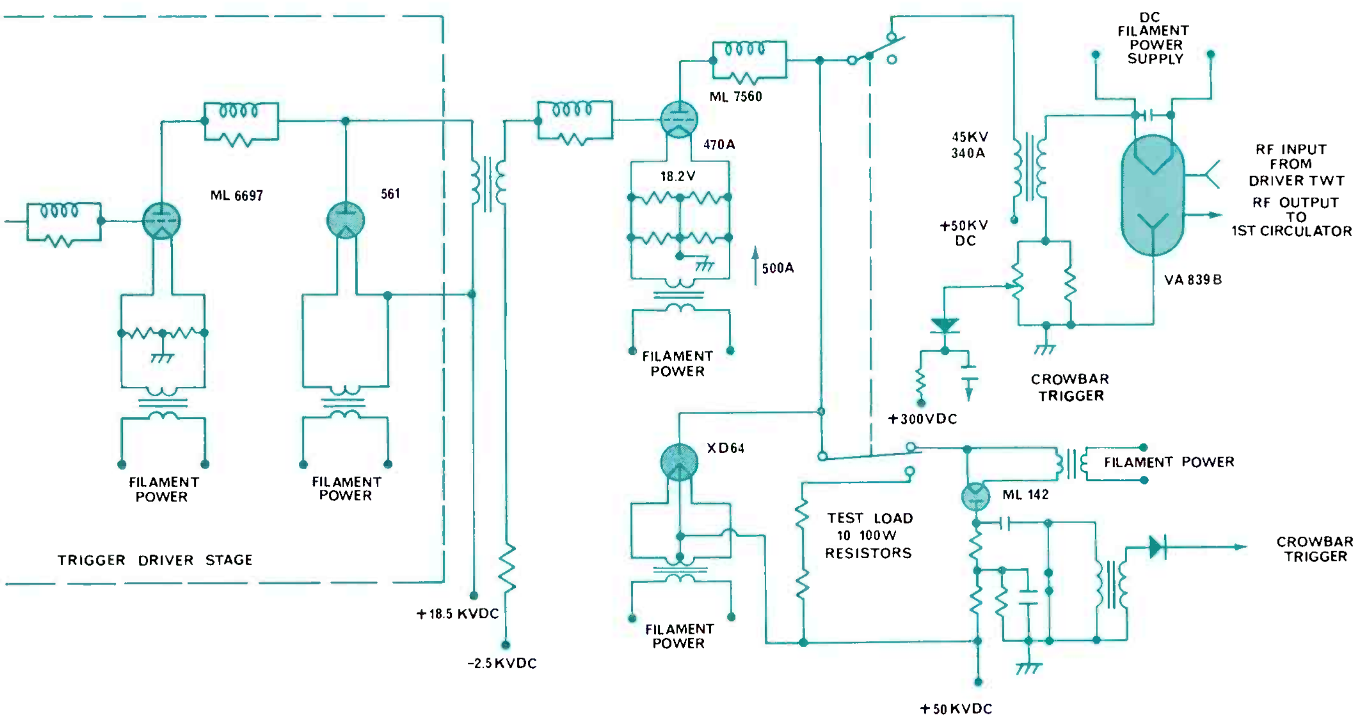


Figure 5 — Plot of ML-7560 plate characteristics with modulator operating point and load line included.

Figure 4 — Simplified schematic of final modulator amplifier.



klystron efficiency is 34% with a power gain of approximately 35 db. Klystron beam focusing is performed by a four-coil electromagnet supplied by four current-regulated and individually adjustable power supplies. The klystron and its electromagnet are mounted on top of the modulator output pulse transformer, and the entire assembly is packaged within a retractable lead enclosure for x-ray protection. Cooling of the klystron and its electromagnet is accomplished along with other transmitter components by a closed-loop cooling system (see Figure 12).

Final Amplifier Modulator

The final amplifier modulator design problem was the most difficult encountered in the overall design of the transmitter. The design was made significantly simpler, however, by the use of a Machlett ML-7560 triode amplifier as the switch tube. Through the use of the ML-7560 it was possible to switch the full peak and average power of 15.7 megawatts and 37 kilowatts, respectively, with a single modulator switch tube. In fact, the modulator employing a single ML-7560 triode is capable of producing 25% more power than is required by the final amplifier. This feature provides both a conservative safety margin for present final amplifiers as well as considerable growth potential for possible future final amplifiers. Figure 4 is a simplified schematic of the final amplifier modulator showing the principal voltages and currents of interest. The ML-7560 is operated at 48 kVdc and produces an output pulse of 45 kv at 340 amperes across the primary of the output pulse transformer. The ML-7560 is driven by a trigger driver which provides a grid pulse of 2.2 kv positive at 205 amperes. Figure 5 is a plot of the ML-7560 plate characteristics with the modulator operating point and load line included. The ML-7560 is driven into saturation to reduce the trigger driver pulse voltage droop, ringing, and ripple being transferred to the output pulse. This technique simplifies the design of the trigger driver and its power supply. Figure 6 is a photograph of the ML-7560 mounted in the modulator cabinet. Also shown in the photograph is the final stage of the trigger driver which employs a Machlett ML-6697 triode as the switch tube. The ML-7560 is water cooled, with a ceramic crock connected in series to provide a 30-foot column of water for insulation purposes.

Output Pulse Transformer

The modulator configuration shown in Figure 4 has advantages from the point of view of modulator design, (for example, the cathode of the ML-7560 is held at ground potential, therefore permitting the trigger driver to be

Figure 6 — ML-7560 in modulator cabinet; shown also is ML-6697 switch tube.

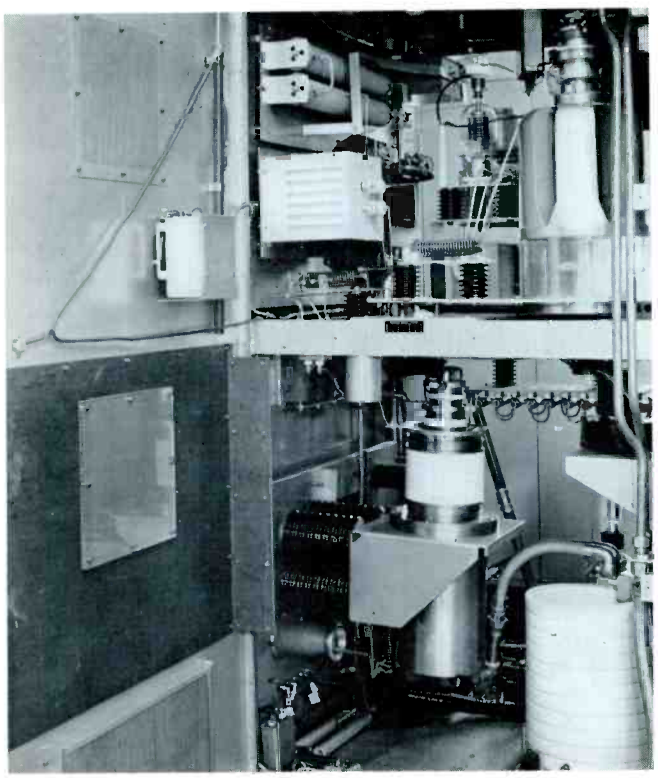
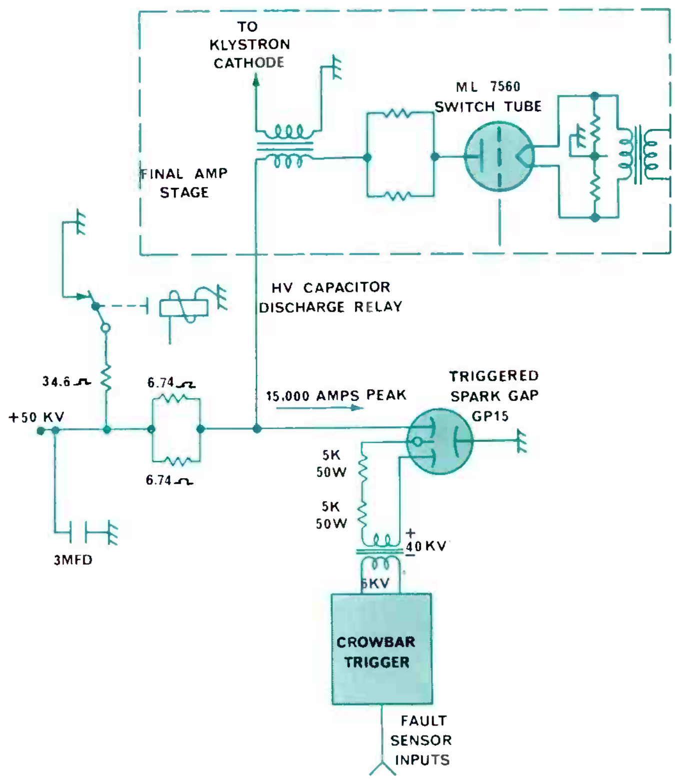
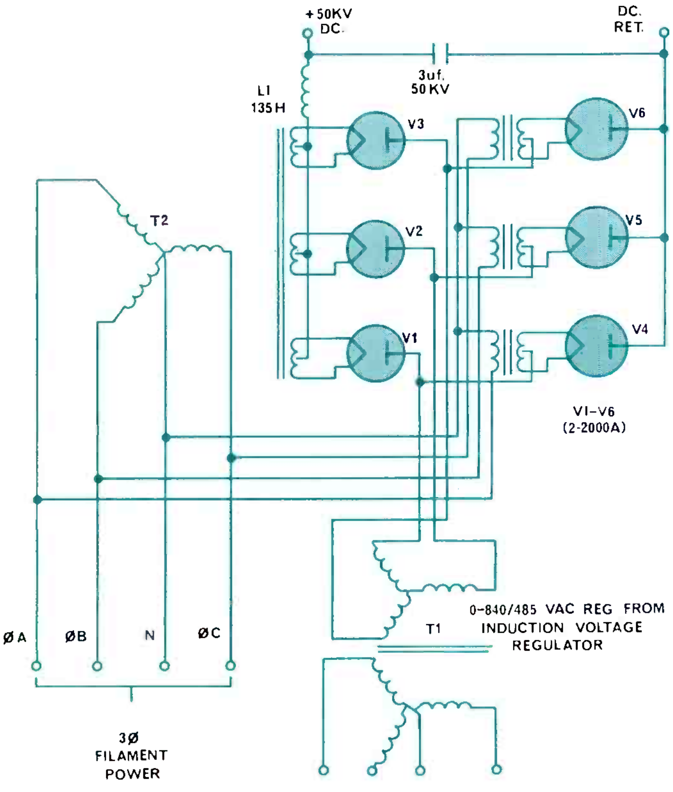


Figure 7 — Simplified schematic of crowbar circuit used to protect klystron and modulator tube.



grounded), but, however, presents a problem from the point of view of pulse transformer design. The modulator configuration chosen requires that the pulse transformer be designed for 50 kVdc between primary and secondary which requires, of course, a relatively large spacing between transformer primary and secondary. This large spacing creates a relatively high transformer leakage inductance. The combination of this high leakage inductance and the high energy being switched results in significant energy being stored in the leakage inductance at the end of the output pulse, as much as 3 joules. Since a modulator is generally designed to gate off the switch tube abruptly, this stored energy will produce an extremely high voltage backswing at the plate of the modulator switch tube, ML-7560. This backswing voltage is difficult to clip by conventional clipping diodes since the primary current flowing just before the end of the output pulse is 340 amperes and this current must be picked up by the clipping diode. The backswing voltage will add to the power supply voltage causing the plate voltage on the ML-7560 to go as high as 100 kv. This, clearly, would be an intolerable situation. The fact that the ML-7560 has ample reserve plate dissipation, under the modulator operating conditions, provided the solution to this dilemma. The ML-7560 is gated off more slowly allowing the energy stored in the leakage inductance to be dissipated primarily in the ML-7560 plate. An ML-7560 plate circuit fall time of approximately 0.5 μsec is required to accomplish this. This technique somewhat increases the dissipation in the klystron collector due to the increased fall time. The usual backswing related to the energy stored in the transformer magnetizing inductance is handled by the conventional backswing clipping diode. Other modulator configurations such as grounding the pulse transformer primary and "floating" the switch tube were considered, but discarded due to the complexities of the trigger driver design and packaging.

Figure 8 — Simplified schematic of high voltage power supply.



Final Amplifier Trigger Driver

The final amplifier trigger driver is required to pulse the ML-7560 grid to a positive voltage of 2200 volts peak at a current of 205 amperes, and to overcome the negative 2500 volts bias applied to the ML-7560 grid. An output pulse, therefore, of 4700 volts is required at 205 amperes or approximately 1 megawatt peak power and 2.3 kW average power. The entire trigger driver was designed to operate from a single high voltage power supply. A Machlett ML-6697 was employed in the final stage of the trigger driver and provides the required driving pulse with ample plate current and plate dissipation margin to assure long tube life and reliable operation.

Final Amplifier Bias Circuit

A single supply is provided for biasing the various stages of trigger driver and modulator. The major problem in the design of a bias supply is the reverse current flowing into the supply as a result of the high grid currents being drawn in the modulator and trigger driver grid circuits. As much as 0.5 amperes average reverse current is produced by the ML-7560 alone. This current, of course, varies directly as the modulator pulse repetition frequency and the pulse width. To provide proper regulation, the bias supply employs a "brute-force" technique, using a heavy bleeder current to "swamp" the effects of varying grid return currents.

Modulator Fault Protection

When voltages in the order of 50 kVdc and 140 kv pulse are employed it should be expected that there may be an occasional spark in the vacuum tubes such as the klystron and switch tube. Because of the very high energy stored in the high voltage power supply output capacitance for a modulator of this type, such a spark would be catastrophic unless suitable protection circuitry is provided. Figure 7 is a simplified schematic of a "crowbar" circuit included to provide this protection. The circuit short circuits the output of the power supply and discharges the power supply energy storage capacitors in the event of a power supply load fault. The crowbar reaction time is approximately two μsec when triggered from either of two fault detection circuits. The fault detection circuits sense switch tube voltage drop and

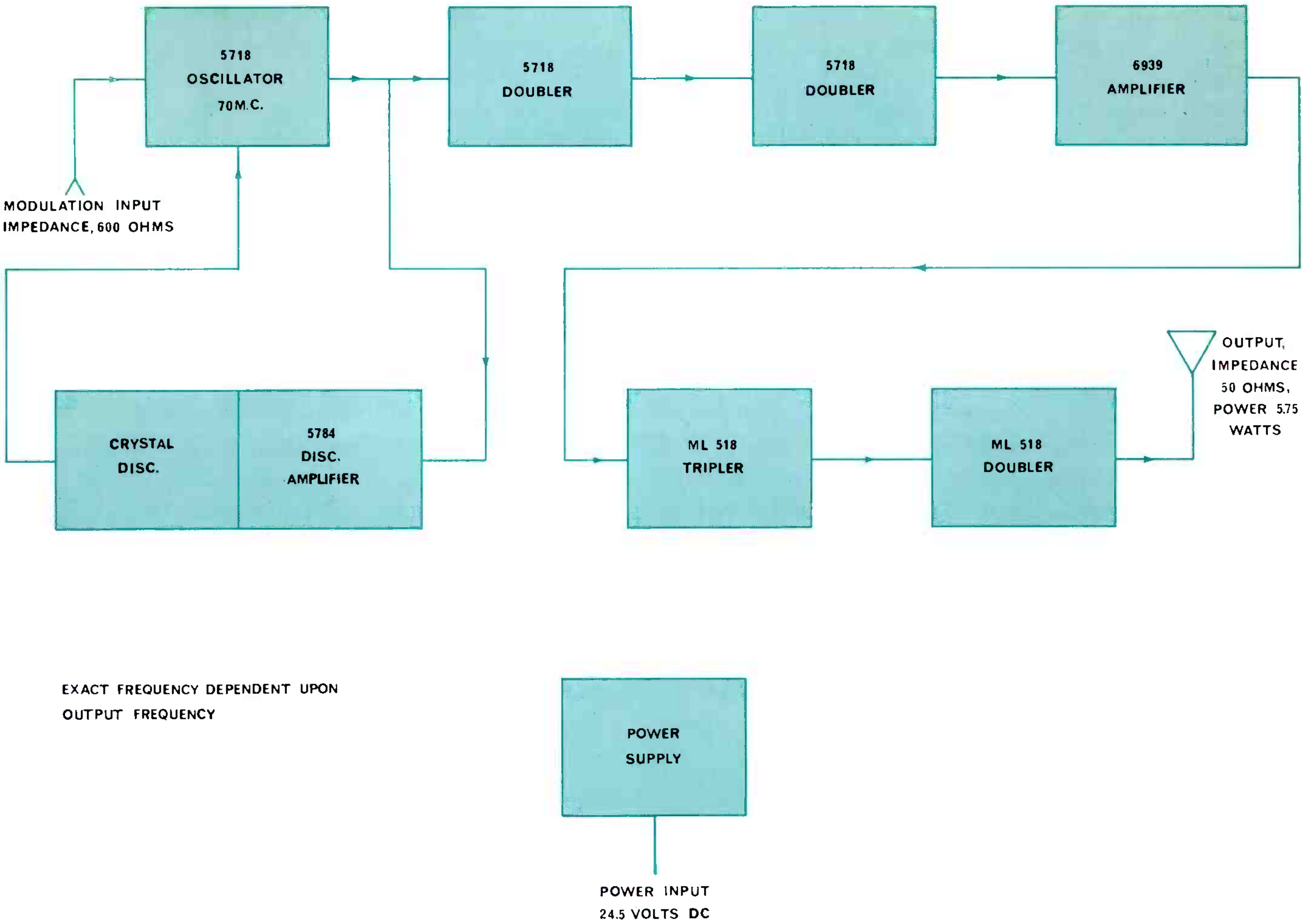


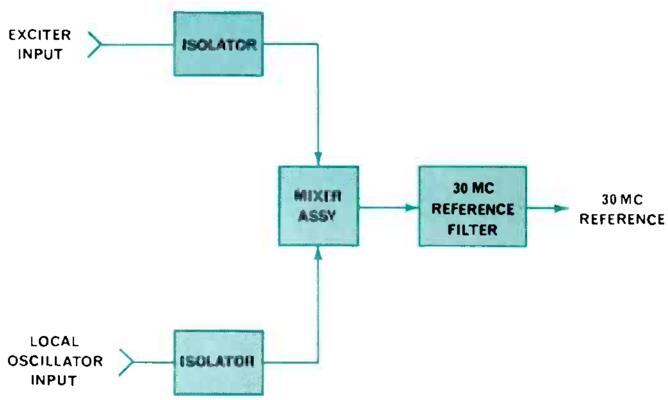
Figure 9 — Block diagram of transmitter exciter.

peak klystron current. In the event of a switch tube spark, the switch tube voltage drop will decrease to nearly zero. This action will trigger the crowbar circuit and short circuit the power supply output voltage. Since, under these conditions, the pulse transformer is between the switch tube and the crowbar, the switch tube circuit will appear as a relatively high impedance compared with the crowbar triggered spark gap and the current will stop flowing in the switch tube and will be conducted to ground by the spark gap. In the event of a klystron arc the peak klystron current will increase above its normal limit. This will also result in triggering of the crowbar and short-circuiting of the power supply output voltage.

ML-7560 Filament Circuit

The ML-7560 employs a thoriated-tungsten filament-cathode which draws 450 amperes of heater current. The presence of this relatively high heater current plus approximately 550 amperes of pulse cathode current presents some interesting filament circuit problems. It is desirable to provide a pulse current path that creates approximately equal pulse current in the two filament conductors. The conventional means of accomplishing this is to ground the center

Figure 10 — Block diagram of coherent signal system for data processing equipment.



tap on the heater transformer secondary and bypass the two ends of the secondary to the center tap with capacitors to provide equal low impedance paths to ground for the pulse cathode current. Since the voltage developed across these capacitors due to the current flowing during the pulse subtracts from the switch tube grid driving voltage, droop in the output pulse voltage is created. The standard technique to reduce this problem is to provide sufficiently large capacitors to reduce this voltage build-up to some reasonable value. With 550 amperes of pulse cathode current, however, the size of these capacitors becomes too large to be considered. Instead of bypass capacitors, 0.45 ohm bypass resistors are employed. Approximately 110 volts is subtracted from the grid driving voltage as a result of pulse current. This voltage is, however, a constant during the pulse and does not create voltage droop in the output pulse. This technique would be prohibitive in terms of power loss in circuits employing switch tubes which consume a relatively small amount of heater power since approximately 300 watts is dissipated in these resistors due to the filament voltage across them alone. This power loss, however, represents only 5% of the heater power of the ML-7560 and is, therefore, not significant. Figure 4 includes the filament circuit showing the voltage and currents of interest. This same technique is also employed in the filament circuit of the ML-6697 in the trigger driver.

Switch Tube Dummy Load

During the installation of a new ML-7560 into the modulator it is desirable, initially, to pulse the tube into a high impedance, low current load instead of its normal high current load. This is because a new tube is likely to spark more frequently at first due to shipping shocks and vibration. A 30,000 ohm resistive dummy load is included in the final modulator for this purpose. During operation into the dummy load the crowbar triggering circuit is disconnected to allow the ML-7560 to spark without triggering the crowbar. This procedure allows the sparks to burn out at a safe current level without damage to the ML-7560.

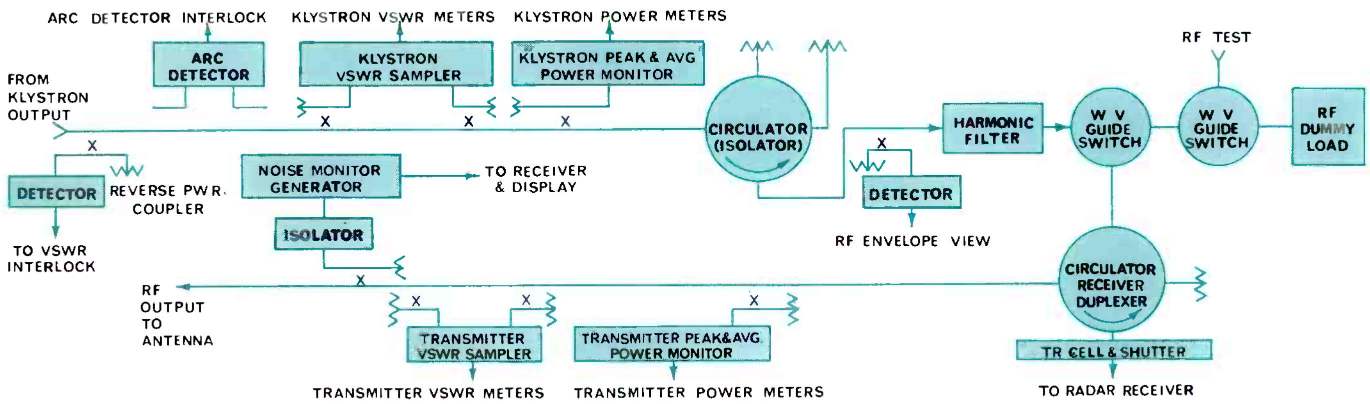
Final Amplifier High Voltage Power Supply

The final amplifier high voltage power supply is designed to deliver up to 50 kVdc at currents up to 1.2 amperes. The power supply is designed to have a maximum output ripple voltage of 0.05% and to have a maximum short circuit current of 20 amperes. The dc output voltage is regulated to within ±1% by an induction voltage regulator controlling the primary voltage supplied to high voltage power supply. The induction voltage regulator is controlled by a differential circuit that senses the high voltage output and compares it to a reference voltage which is produced by a corona regulator tube. Figure 8 is a simplified schematic of the high voltage power supply.

Driver Amplifier Stage

The driver amplifier stage employs a Varian Associates VA-128B TWT as the microwave power amplifier. The VA-128B produces 3.2 kW peak power to drive the final amplifier, at a gain of approximately 33 db. The VA-128B is provided with a modulating grid and, therefore, can be modulated with a low power, high performance modulator. The modulator produces a 900 volts peak pulse with a rise time of less than 50 nanoseconds and a fall time of less than 100 nanoseconds. The top of the modulator pulse voltage is clipped to provide an extremely rectangular flat top driving pulse to the VA-128B grid. The high voltage power supply for the driver amplifier stage is a negative, electronically regulated supply with an output ripple of less than 100 millivolts. Two variable attenuators are provided in the microwave link between the driver and final amplifiers. The first attenuator provides for adjustment of the peak rf drive power to the final amplifier. The second performs the function of the power programmer which varies the transmitted

Figure 11 — Block diagram of SPANDAR transmitter microwave system.



output power from full output to —40 db.

Buffer Amplifier Stage

The buffer amplifier stage employs a Huggins PA-10A TWT as the microwave power amplifier. The PA-10A produces 10 watts peak power to pulse the driver amplifier at a gain of approximately 33 db. The width of the rf pulse is designed to overlap the driver amplifier modulator pulse width in time, thereby assuring that the VA-128B TWT has full rf drive throughout the pulse period. The PA-10A is provided with a modulating grid and, therefore, can be modulated with a low power modulator.

Exciter Stage

Figure 9 is a block diagram of the transmitter exciter or master oscillator. As shown in the block diagram five fixed frequency precision oscillators are provided. These oscillators, operating between 4.6 and 4.9 megacycles, provide the transmitter frequency stability of 1 part in 10^9 short term, 1 part in 10^6 long term. The outputs of the five fixed frequency oscillators are multiplied up six times to the vicinity of 28 Mc by five independent multipliers. Also included as part of the exciter is a Manson Laboratory crystal synthesizer which provides a variable frequency over the frequency band of 27 to 29 Mc in 1 kc steps. The output of one of the five multipliers or the crystal synthesizer is then selected through relays to be connected to the input of a one-hundred times broadband multiplier. The X100 multiplier is divided into three stages, the last stage of which is a X5 varactor multiplier. The output of this multiplier is, of course, at the desired transmitter frequency between 2700 and 2900 megacycles.

Local Oscillator

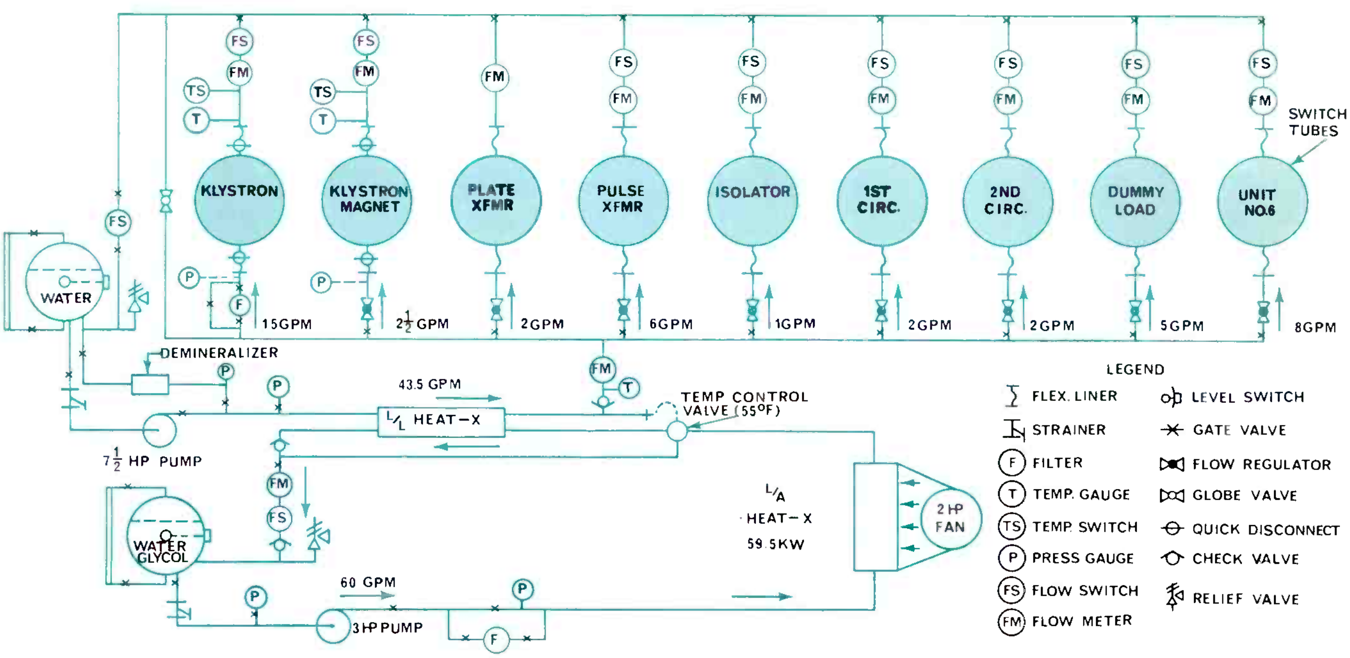
The local oscillator provides an rf signal located 30 Mc above the transmitter frequency. The local oscillator is essentially identical to the transmitter exciter providing the same frequency stability and frequency precision. A Huggins HA-30 TWT is added to amplify the output of the local oscillator to a power level of 100 milliwatts CW. The local oscillator output is used in the radar receiver mixer.

A completely separate local oscillator is employed instead of the more conventional oscillator-mixer configuration to avoid the problem of multiple mixer outputs being introduced into the transmitter channel and being amplified by the broadband transmitter.

Coherent Output

Radar signal data processing frequently requires the use of an IF frequency reference signal that is phase coherent with the transmitted rf signal and the receiver local oscillator frequency. To obtain this signal the output of the transmitter exciter and local oscillator are mixed to produce a coherent output signal at 30 Mc, as shown in block diagram form in Figure 9. The isolators shown are employed to prevent the transmitter frequency from leaking into the local oscillator output and the local oscillator frequency from leaking into the transmitter exciter output, and be, thereby,

Figure 12 — Block diagram of transmitter cooling system showing coolant flow levels in various components of interest.



amplified by the broadband transmitter power amplifiers. Since the coherent signal is derived from the local oscillator and exciter, it has the same frequency precision and stability.

Microwave System

Figure 11 is a block diagram of the SPANDAR transmitter microwave system. Following are brief descriptions of some of the components included.

Arc Detector

A waveguide arc detector is provided to protect the final amplifier klystron from damage due to a possible waveguide arc. The arc detector senses the light of an arc in the waveguide by means of a light sensitive diode. The signal produced is amplified and used to interrupt the trigger to the driver amplifier modulator within one interpulse period.

Klystron VSWR Monitor

The klystron VSWR monitor provides continuous measurement of the VSWR seen by the klystron. A second identical monitor is included at the transmitter output to monitor antenna VSWR. This monitor is also employed during antenna tuning procedures.

Power Monitor

A peak and average power monitor is provided to monitor the klystron output power. The power monitor employs a hot-cathode vacuum microwave diode as a sensing element and provides continuous peak and average power measurement over a 40 db dynamic range in four 10 db steps.

Waveguide Switches

Two waveguide switches are employed to switch among the transmitter dummy load, the output to the antenna and a test port to which test loads can be connected. The rf dummy load provided is capable of operation at full transmitter power.

Receiver Duplexer

A ferrite circulator is included to perform the function of a receiver duplexer. Also included on the receiver arm of the circulator is a receiver protector TR cell and shutter.

Noise Figure Monitor

A noise figure monitor system is included to provide continuous measurement of receiver noise figure.

Waveguide Pressurizer

A waveguide pressurizer-dehydrator system is employed to pressurize the radar waveguide system with clean-dry sulphur-hexafloride at a pressure of 35 PSIA. The system is the heatless dryer, recirculating type manufactured by Applied Pneumatics.

Cooling System

Transmitter cooling is provided by a two stage closed loop system employing a 50-50 water-glycol solution on the outside of the transmitter building and distilled water on the inside. A liquid-to-air heat exchanger outside the building transfers the heat from the water-to-glycol loop to the outside air, and a liquid-to-liquid heat exchanger, inside the building, transfers the heat from the water system to the water-glycol system. The cooling system is capable of dissipating a maximum heat load of 75 kW at an outside air temperature of 120°F. Figure 12 is a block diagram of the transmitter cooling system showing the coolant flow levels in various components of interest.

Conclusion

The SPANDAR transmitter has fulfilled all of the basic requirements of a transmitter for a long range tracking radar. The transmitter provides a minimum of 5 megawatts across its operating band and up to 7 megawatts in the center of the band. It is completely remote controlled and is equipped with many fault diagnostic type indicators. During the tracking operation of the SPANDAR radar a small control panel in the Master Radar Control console provides the radar operator with all the necessary transmitter controls, such as frequency, pulse width and output power. Frequency and pulse width are changed by a push button control and output power by the turning of a knob.

The transmitter has been in operation at Wallops Island for nearly one year and has logged well over 1000 hours of operation. Although there have been some minor difficulties during the first year's operation, the transmitter has never failed during the tracking of a vehicle.

The same klystron and ML-7560 switch tube are in operation that were in operation when the equipment was accepted by NASA. The ML-7560 has actually improved performance with age. The number of transmitter "kick-outs" due to sparking of the ML-7560 has decreased with time. The problem of possible sparking of the switch tube or klystron caused some concern during the design of the transmitter, particularly if such a spark were to occur during a tracking operation. A fast acting automatic fault clearing circuit was designed to reduce this problem. The fault clearing circuit automatically restores the transmitter to full power output in the event of such a spark during a rocket flight. Restoration of power is complete within 2 seconds after the fault. Testing of this circuit performance has indicated that the radar operator can barely discern that a fault has occurred during the track. Also included is a "flight short" switch which disables all non-critical transmitter interlocks to assure that the transmitter is not shut down during a tracking operation due to a minor failure such as a door interlock.

In conclusion, the transmitter has provided NASA's Wallops Station the power, performance and reliability required for a long-range tracking radar.

New Machlett Developments

With this issue, CATHODE PRESS introduces a new section which will report, in brief, the latest Machlett electron tube designs and improvements.

ML-7480

General purpose, vapor-cooled triode for 50 - 75 kW service to 30 Mc

For industrial heating and AM broadcast applications, the ML-7480 is designed for use as an rf power amplifier and oscillator. Features include: a unique vapor-cooled anode design capable of dissipating 80 kW; a sturdy self-supporting, stress-free, thoriated-tungsten filament; and ceramic envelope, coaxial terminal structure.

Maximum Ratings as RF Power Amplifier and Oscillator Class C Telegraphy

DC Plate Voltage	16000 v
DC Grid Voltage	—3200 v
DC Plate Current	11 amps
DC Grid Current	2.0 amps
Plate Input	140 kW

Typical Operation

DC Plate Voltage	15000 v
DC Grid Voltage	—1600 v
DC Plate Current	7.0 amps
Driving Power, Approx.	0.60 kW
Power Output	80 kW

ML-8317

General purpose, forced-air-cooled triode for 100 kW service to 30 Mc and pulsed applications

Designed primarily for high power, shortwave communications, the ML-8317 is capable of more than 100 kW carrier output in a plate-modulated amplifier. In SSB service, it is capable of 100 kW peak envelope power output under two-tone modulation, and more than 500 kW PEP under 16-tone conditions. In pulse service it is capable of 15 Mw typical output power. Employs high-efficiency radial-fin anode cooler.

Maximum Ratings RF Power Amplifier and Oscillator

DC Plate Voltage	20000 v
DC Plate Current	20 amps
Plate Input	250 kW
Plate Dissipation	60 kW

Maximum Ratings Pulse Modulator or Pulse Amplifier

DC Plate Voltage	50 kv
Peak Plate Voltage	55 kv
Pulse Cathode Current	550 amps
Plate Dissipation	60 kW

DP-18

High power triode for pulse service to 27 Mw

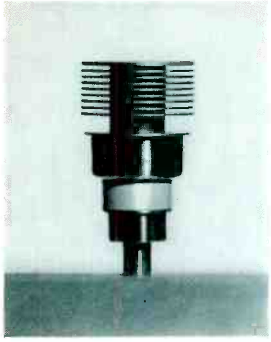
Designed to operate primarily as a switch tube in hard-tube modulators — for radar and similar applications. Employs ceramic envelope, thoriated-tungsten cathode, and forced-oil-cooled anode.

Maximum Ratings Pulse Modulator or Pulse Amplifier

Peak Plate Voltage	180 kv
Cathode Current	225 amps
Plate Dissipation	20 kW

Typical Operation

DC Plate Voltage	170 kv
DC Grid Voltage	—150 v
Pulse Positive Grid Voltage	1300 v
Pulse Plate Current	135 amp
Pulse Grid Current	55 amp
Pulse Driving Power	100 kW
Pulse Power Output	20 Mw
Pulse Output Voltage	150 kv



ML-8403

UHF planar triode provides frequency stable capability and high cathode current service to 3 Gc

ML-8403 is a ruggedized, high-cathode-current, frequency-stable anode, high-mu planar triode. It employs ceramic-to-metal construction, and is designed for use as a grid-pulsed, plate-pulsed, or CW oscillator, frequency multiplier, or amplifier in radio transmitting service from low frequency to 3 Gc.

Maximum Ratings
CW Oscillator and Amplifier

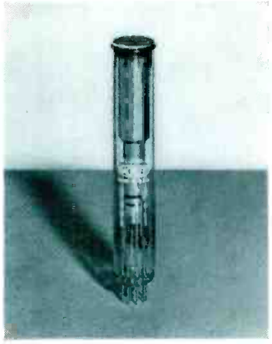
DC Plate Voltage	2000 Vdc
DC Grid Voltage	—150 Vdc
Plate Dissipation (forced-air-cooling)	100 W

Maximum Rating
Plate-Pulsed Oscillator and Amplifier

Peak Plate Pulse Supply Voltage	3500 v

Maximum Ratings
Grid-Pulsed Oscillator and Amplifier

Pulse Length	6 usec
Duty Factor	0.0033
DC Plate Voltage	2000 Vdc
Peak Plate Current from dc Supply	5.0 a



ML-7351A

Highest sensitivity, tipless vidicon for low light level or slow-scan applications

ML-7351A is a tipless vidicon designed to provide extremely high sensitivity under 2870°K illumination. At 6000 Å the output is 25 ua/uW.

For slow-scan TV; operates with lower dark currents — at ASA 1200 a dark current of only 0.05ua is required (approx. ¼ of comparable tubes).

Operates with less than 0.05 ft-c. faceplate illumination, or average scene illumination of less than 2.5 ft-c. with f/2.0 lens.

Dimensions: dia. 1⅛″; length 6¼″.

ML-8443

Compact 5″ DVST for airborne radar applications where space is a premium

ML-8443 direct-view storage tube offers bright visual display of half-tones and compact size without any sacrifice in performance.

Size: 5″ dia. 8″ max. length

Resolution: 70 lines/in

Storage Time: 1 minute minimum

Deflection: Magnetic

Focus: Electrostatic

Writing Speed: 200,000 in/sec

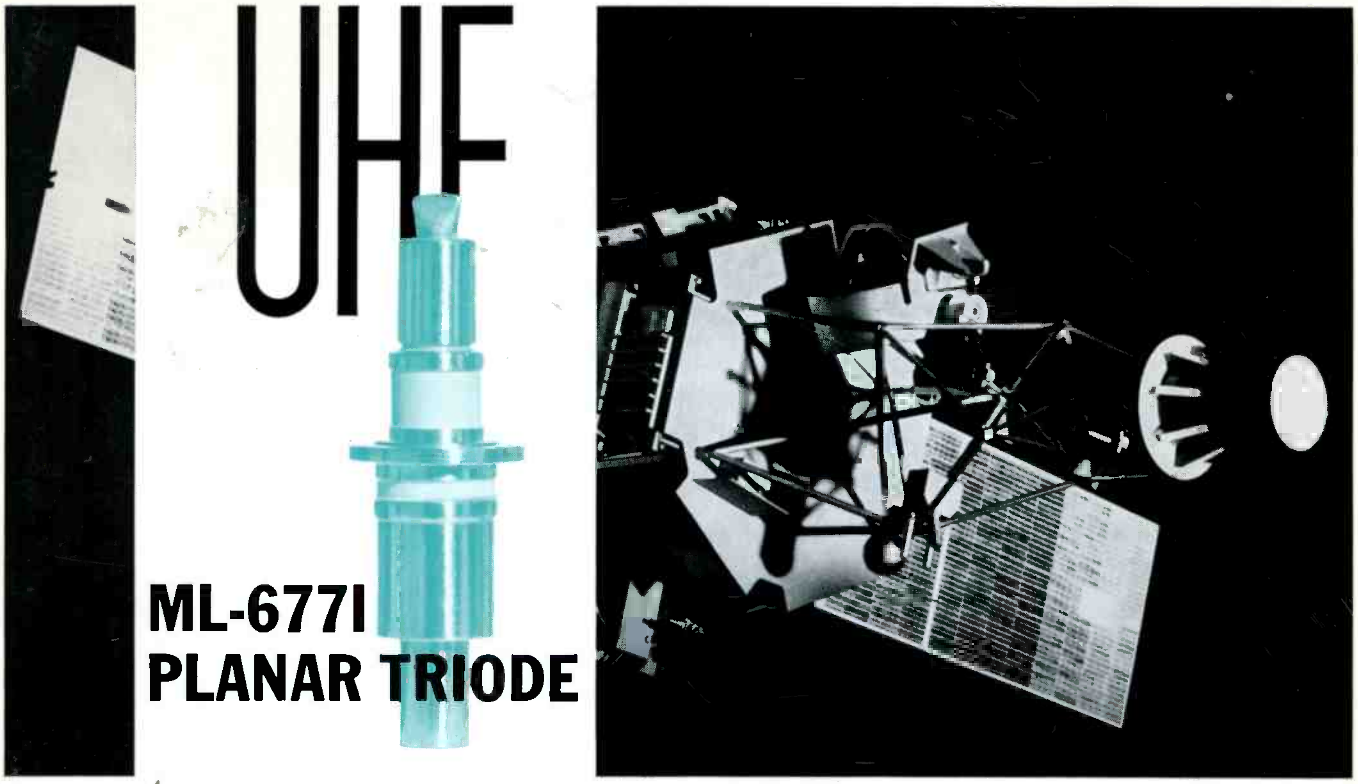
Brightness: (At 6.5 kV view-screen potential) 1000 ft.L

ML-2058G

High resolution 2″ vidicon

Operates with conventional image orthicon deflection coils.

Offers 50% amplitude modulation at 1100 TV lines. Limiting resolution is 2000 TV lines. Also available with x-ray sensitive photoconductor. Maximum length is 12 in.



The **only** electron tubes aboard the **MARINER II** in rf circuits are the Machlett ML-6771 planar triodes, adapted specifically for this application

Space communications from the Mariner II Venus experiment were successfully maintained by the two 3-watt transmitters and ¼ watt driver, each powered by a Machlett special ML-6771 planar triode.

High reliability* is the reason that Jet Propulsion Laboratory, designer of the rf cavities, has chosen Machlett planar triodes.

*High reliability means, here, excellent cathode emission stability; and uniform long-life, performance achieved through the highest Quality Control standards.

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UHF Planar Triode Brochure

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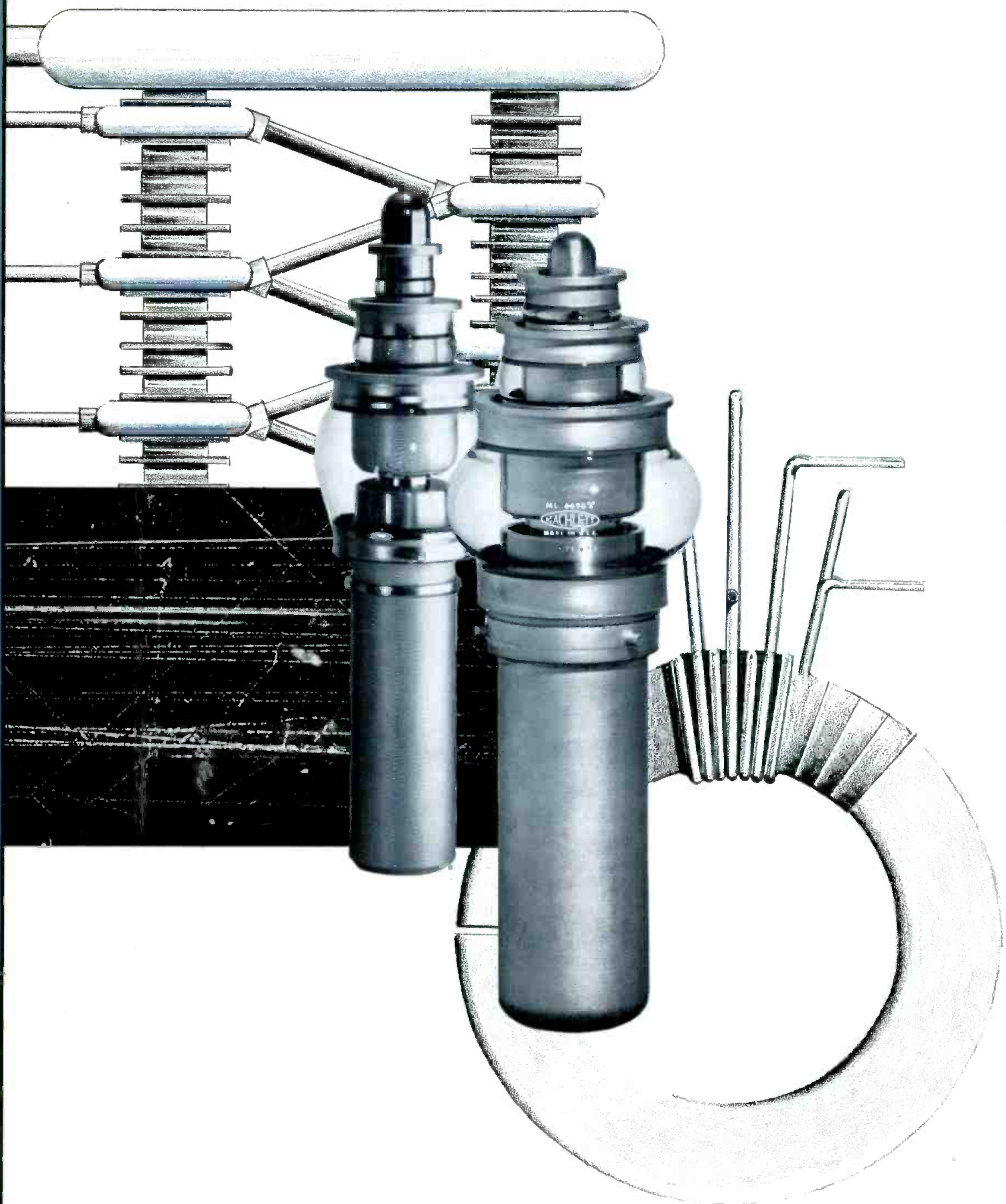

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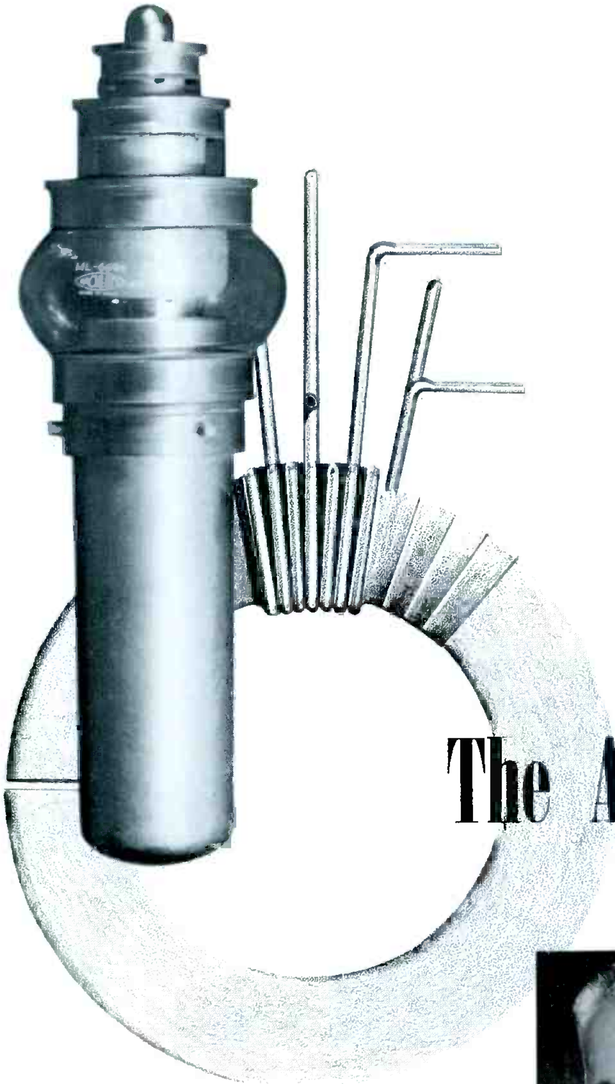
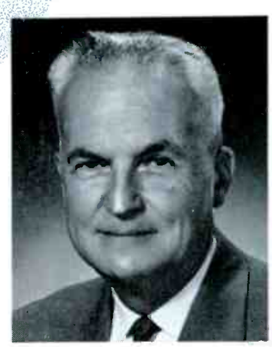


The Alternating Gradient



R. H. RHÉAUME

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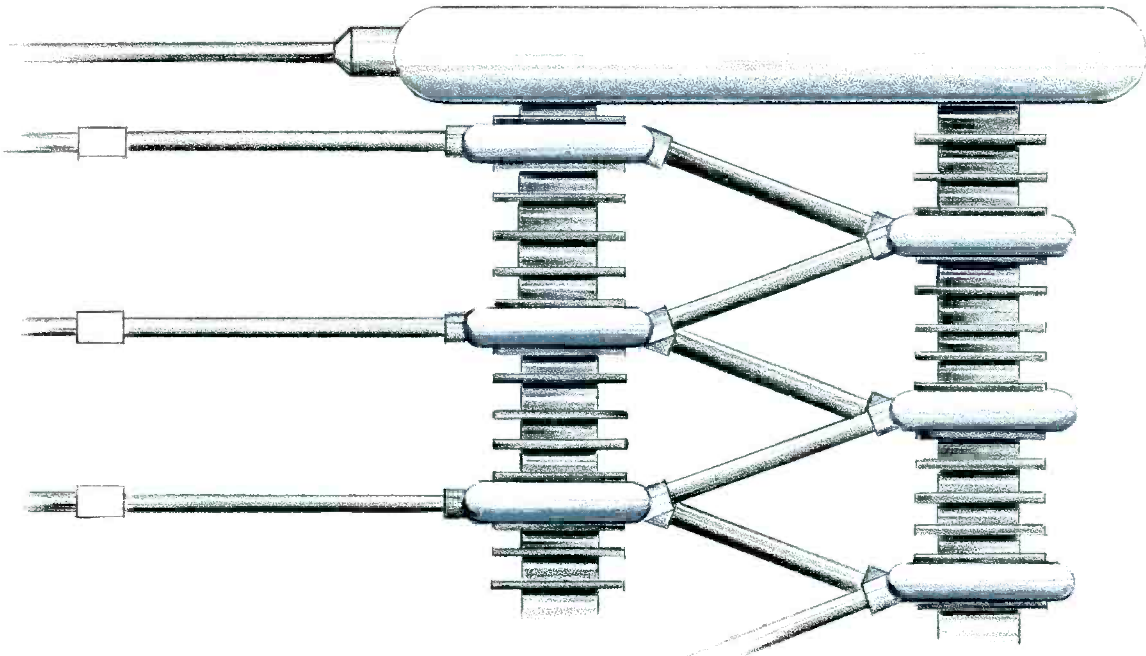
His professional connections have included Bell Telephone Laboratories, Western Electric Company, Machlett Laboratories, and Hanovia Chemical and Manufacturing Co., Electrical Division. He is now an electrical engineer on the scientific staff of the Brookhaven National Laboratory.



Synchrotron and Machlett Power Tubes*

By R. H. RHÉAUME, *Brookhaven National Laboratory*
Associated Universities, Inc.
Upton, L. I., N. Y.

In the ferrite-coupled wideband power amplifier stages of the Brookhaven Alternating Gradient Synchrotron, ML-6424 and ML-6696 coaxial triodes help accelerate protons to an energy of 33 billion electron volts.

Introduction

From the early days of x-rays there has been a Machlett tradition of service to atomic science and technology through contributions to the art of high vacuum tubes[1]. Modern super-energy particle accelerators are themselves very large high vacuum tubes designed for studying subatomic particles, the building blocks of the universe. The most important of these high energy physics research machines, the cyclic particle accelerators, rely upon high-power electron tubes for radio frequency accelerating energy. The largest accelerator yet to be built, the Brookhaven Alternating Gradient Synchrotron, requires not only more, but also more precisely controlled rf accelerating power than former machines, and employs ML-6424 and ML-6696 coaxial power triodes toward this purpose.

Brookhaven and the AGS

Studies of atomic nuclei form a major part of the research program of Brookhaven National Laboratory, a national center for fundamental and applied research in the nuclear sciences and related subjects situated at Upton, Long Island, New York. This research, which is basic to nuclear science, broadly involves all the major machines and ranges from measurements of the masses and other properties of undisturbed nuclei to observations of the violent disruptions resulting from nuclear fission and from bombardment of targets by ultra-high energy particles. Workers in this field use accelerators of various designs at many different energy levels, since the experimental results vary with the energies of the bombarding particles. With the aid of the more recent machines, new particles such as mesons and hyperons have been discovered; the latest discovery has been the verification of the existence of two kinds of neutrinos and their corresponding anti-particles by means of the Alternating Gradient Synchrotron, or AGS. A summary of known fundamental particles and interactions is presented in Table I.

*Work carried out under contract with U. S. Atomic Energy Commission.

[1]Machlett Cathode Press, Memorial Issue, 1955.

TABLE 1 Fundamental

CLASS	NAME	PARTICLES	ANTI-PARTICLES
BARYONS STRONGLY INTERACTING FERMIONS (SPIN = 1/2 ħ)	CASCADE HYPERON (ISOTOPIC SPIN T = 1/2)	S = −2: Ξ^0, Ξ^-	S = +2: $\bar{\Xi}^+$, $\bar{\Xi}^0$
	SIGMA HYPERON (T = 1)	Σ^+ ($T_3 = +1$); S = −1: Σ^0 ($T_3 = 0$), Σ^- ($T_3 = -1$)	$\bar{\Sigma}^+$ ($T_3 = +1$), $\bar{\Sigma}^0$ ($T_3 = 0$); S = +1; $\bar{\Sigma}^{-1}$ ($T_3 = -1$)
	LAMBDA HYPERON (T = 0)	S = −1: Λ^0	S = +1: $\bar{\Lambda}^0$
	NUCLEON (PROTON-NEUTRON) (T = 1/2)	p^+ ($T_3 = +1/2$), n^0 ($T_3 = -1/2$); BARYON CHARGE CENTER	$\bar{n}^0$ ($T_3 = +1/2$), $\bar{p}^-$ ($T_3 = -1/2$); ANTI-BARYON CHARGE CENTER
MESONS STRONGLY INTERACTING BOSONS (SPIN = 0)	K MESON (T = 1/2)	HEAVY MESON CHARGE CENTER; S = +1: K^+ ($T_3 = +1/2$), K^0 ($T_3 = -1/2$)	S = −1: $\bar{K}^0$ ($T_3 = +1/2$), K^- ($T_3 = -1/2$); (K; K^0; $\bar{K}^0$
	PI MESON (T = 1)	π^+ ($T_3 = +1$), π^0 ($T_3 = 0$), π^- ($T_3 = -1$)	
LEPTONS WEAKLY INTERACTING FERMIONS (SPIN = 1/2 ħ)	MUON	μ^-	μ^+
	ELECTRON	e^-	e^+ (POSITRON
	NEUTRINO	ν	$\bar{\nu}$
MASSLESS BOSONS	(SPIN = 1 ħ) PHOTON	γ	
	(SPIN = 2 ħ) GRAVITON ?		

REST MASS IN Mev	MEAN LIFE IN SECONDS	DECAY SCHEMES
$\Xi^{\pm} \approx 1320$	1.3×10^{-10}	$\Xi^- \rightarrow \Lambda^0 + \pi^-$
$\Xi^0 \approx 1310$	1.5×10^{-10}	$\Xi^0 \rightarrow \Lambda^0 + \pi^0$
	0.8×10^{-10}	$\Sigma^+ \rightarrow p^+ + \pi^0$ (50 %); $\rightarrow n^0 + \pi^+$ (50 %)
≈ 1190	$< 10^{-12}$	$\Sigma^0 \rightarrow \Lambda^0 + \gamma$
	1.7×10^{-10}	$\Sigma^- \rightarrow n^0 + \pi^-$
1115	2.5×10^{-10}	$\Lambda^0 \rightarrow p^+ + \pi^-$ (67 %); $\rightarrow n^0 + \pi^0$ (33 %)
n 939.5	1.01×10^3	$n^0 \rightarrow p^+ + e^- + \bar{\nu}$
p 938.2	STABLE	
= K^+) 494	1.2×10^{-8}	$K^+ \rightarrow \pi^0 + e^+ + \nu$ (5 %); $\rightarrow \pi^0 + \mu^+ + \nu$ (5 %); $\rightarrow \mu^+ + \nu$ (64 %); $\rightarrow \pi^+ + \pi^0$ (19 %); $\rightarrow 2\pi^+ + \pi^-$ (6 %); $\rightarrow \pi^+ + 2\pi^0$ (2 %)
K_1^0 498	1×10^{-10}	$K_1^0 \rightarrow \pi^+ + \pi^-$ (≈34 %); $\rightarrow 2\pi^0$ (≈16 %)
K_2^0	$\sim 6 \times 10^{-8}$	$K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0$; $\rightarrow 3\pi^0$ (7 %); $\rightarrow \pi^{\pm} + \mu^{\mp} + \bar{\nu}$ (19%); $\rightarrow \pi^{\pm} + e^{\mp} + \nu$ (24%)
π^- 140	2.6×10^{-8}	$\pi^- \rightarrow \mu^- + \bar{\nu}$
π^0 135	2.3×10^{-16}	$\pi^0 \rightarrow \gamma + \gamma$ ($\pi^0 \rightarrow \gamma + e^+ + e^-$ 1 %)
π^+ 140	2.6×10^{-8}	$\pi^+ \rightarrow \mu^+ + \nu$ ($\pi^+ \rightarrow e^+ + \nu$ .01 %)
105.7	2.2×10^{-6}	$\mu^- \rightarrow e^- + \nu + \bar{\nu}$
0.51	STABLE	
0	The neutrinos associated with $\mu^{\pm}$ are different from those with $e^{\pm}$	
0	STABLE	
0	STABLE	NOT DETECTED

Table 1 continued — Fundamental Particles and Interactions

THE INTERACTIONS

GRAVITY

Gravitational "charge" is mass.

Gravitational force between particles negligible.

Force falls off with inverse square of distance-velocity independent - always attractive.

Graviton - agent of force - not detected.

STRONG NUCLEAR

Short range force.

Charge independent.

Strength of force when nucleons touch is over 100 times greater than electric force.

Agent of force is π meson.

ELECTROMAGNETISM

Charge - Q - quantized - either + or —.

Agent of force is photon.

E-M force responsible for atomic and molecular binding, hence for most "forces" of everyday world.

Force is velocity dependent, changing aspect from electrostatic to electromagnetic depending on relative velocity of source and observer.

Force can be attractive or repulsive.

WEAK INTERACTIONS

10^{-13} times weaker than strong nuclear.

Responsible for β-decay radioactivity and particle decays taking longer than 10^{-15} seconds

THE RULES

THE DESCRIPTION OF ALL INTERACTIONS

Is independent of:	*Leading to conservation of:*
Space translation	Momentum
Time translation	Energy-Mass
Space rotation	Angular momentum
Zero of electric potential	Charge
Inverse of space and charge together	Product of space parity and charge reflection
Reversal of time	Time parity
?	Baryons and leptons

THE STRONG AND ELECTROMAGNETIC (BUT NOT THE WEAK) INTERACTIONS

Are independent of:	*Leading to conservation of:*
Reflection of space	Parity
Reflection of charge	Charge parity: T_3 and S

THE STRONG (BUT NOT THE ELECTROMAGNETIC OR WEAK) INTERACTION

Is independent of:	*Leading to conservation of:*
Charge	Isotopic spin, T

THE PARAMETERS

SPIN *S*	In a magnetic field, a particle with spin s can exist in (2s + 1) energy states.
ISOTOPIC SPIN *T*	Interaction with the electromagnetic field separates particles with isotopic spin T into (2T + 1) charged states.
PARITY EVEN OR ODD	The function describing a particle system remains unchanged, except for a possible change of sign, if the sign of all the spatial coordinates is changed. (space reflection). The function has odd parity if it changes sign: even if it does not.
STRANGENESS *S*	The charge centers of the isotopic spin multiplets within the same class are not the same. The "strangeness" number signifies the amount of this displacement. The charge centers for the two classes are chosen to be those for pions and nucleons.
BARYON AND LEPTON NUMBER *b* *l*	The baryons have b = + 1 for particles and b = — 1 for antiparticles. The leptons have l = + 1 for particles and l = — 1 for antiparticles. For baryons and mesons electric charge Q = $\frac{+}{-}$0 electron charge $Q = e \left\| T_3 + \frac{b}{2} + \frac{S}{2} \right\|$

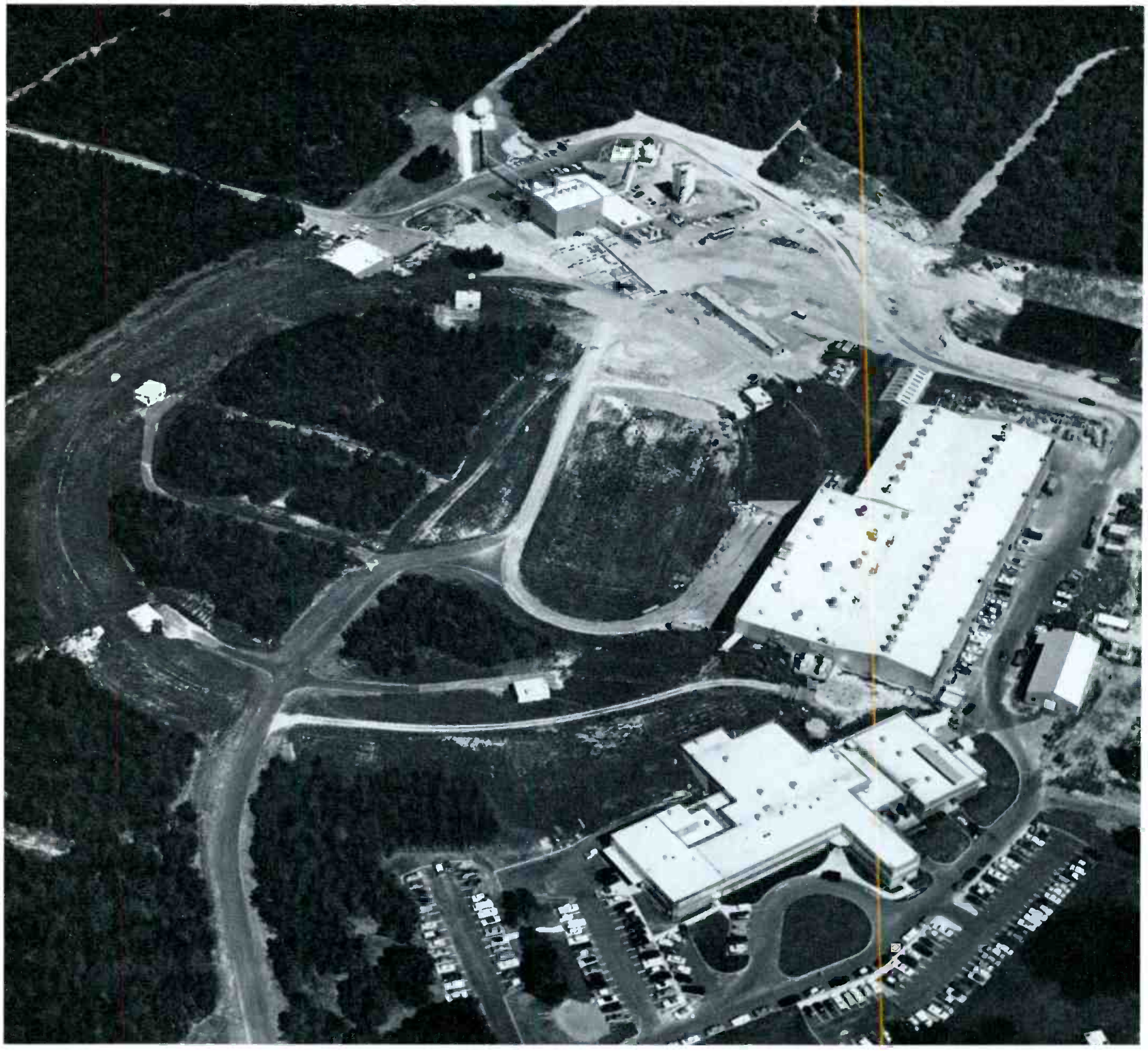


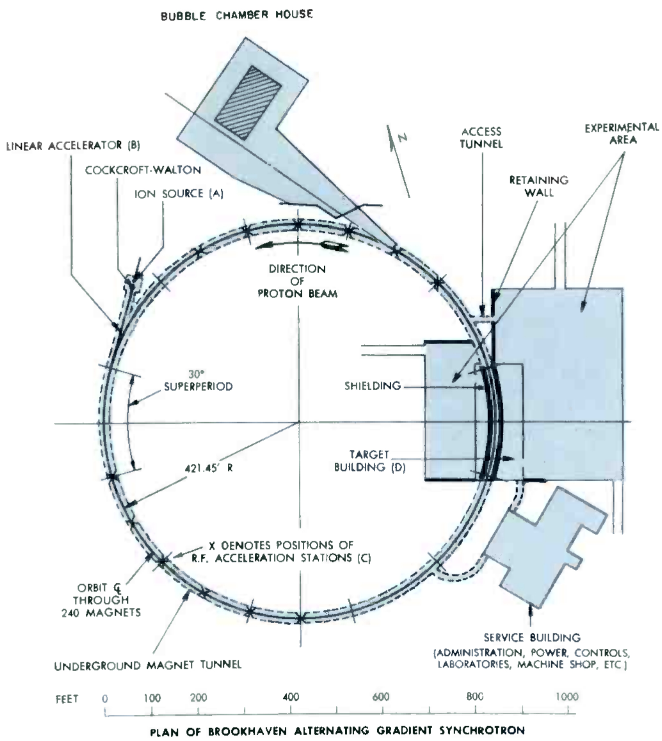
Figure 1 — Aerial view of the Brookhaven AGS.

Description of the AGS

The discovery of the strong-focusing principle made feasible the design and construction of accelerators in the energy range of tens of billions of electron volts. Two such machines now exist in the 28 to 33 billion electron volt range. The first is at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. The second, and somewhat larger, is in operation at Brookhaven National Laboratory, having produced an initial beam of accelerated protons July 29, 1960.

Perhaps the most direct way to describe such a machine is to follow a beam of protons from the point of origin until they attain the full design energy of the machine. An aerial view and a schematic representation of the Brookhaven AGS are given in Figures 1 and 2, respectively. At point (A), Figure 2, protons are obtained by ionizing hydrogen gas in a cold discharge source. Acceleration commences with the raising of these charged particles to 750,000 electron volts (ev) by means of a Cockcroft-Walton generator, illustrated in Figure 3. It is simply a high-potential transformer-rectifier-capacitor-multiplier arrangement with an RC filter for reducing ac ripple.

In the second step, protons from the Cockcroft-Walton generator are accelerated to 50 million electron volts (Mev)



AGS peak energy . . . .
Accelerated particles . . . .
Circumference of synchrotron . . . .
Accelerating cycle . . . .
Ion source . . . .
Preaccelerator . . . .
Injector . . . .
Main bending and focusing magnets . . . .

Magnet power supply . . . .

Vacuum chamber . . . .
Vacuum pumps . . . .

Accelerating stations . . . .

Target building . . . .
Out-door experimental area . . . .
Enclosed experimental area . . . .
Shielding in target building . . . .
Power and control cable . . . .

Figure 2 — Plan of Brookhaven Alternating Gradient Synchrotron.

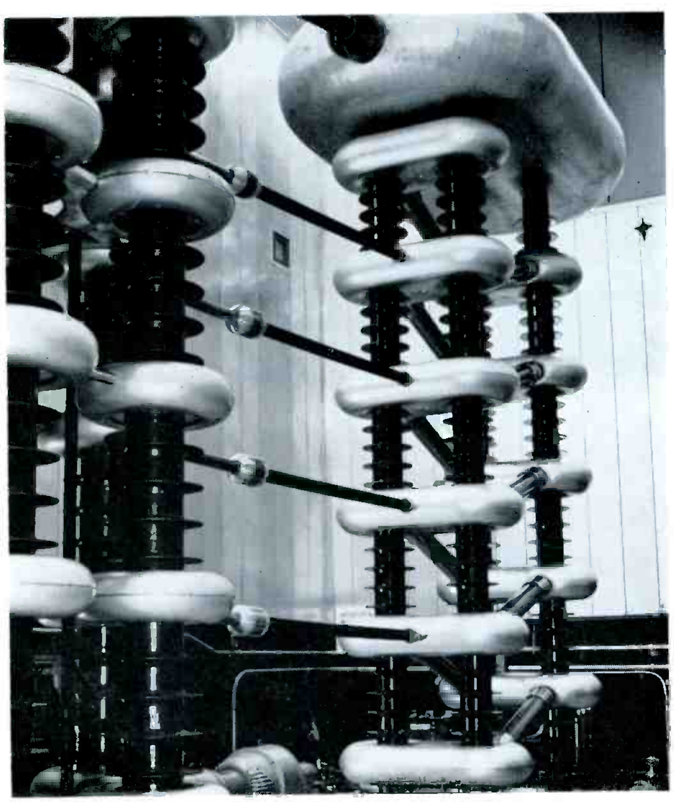


Figure 3 — Cockcroft-Walton generator.

by projecting them down the central axis of the 110-foot linear accelerator tank (Linac), point (B). The interior of this tank, viewed from the low-energy end, is shown in Figure 4. It is approximately three feet in diameter, with 124 high voltage drift tube electrodes axially spaced, shaped, and excited at resonance with several megawatts of long-pulse 200-megacycle rf power to impart the needed beam energy.

From the Linac, the 50-Mev protons are launched into the half-mile closed vacuum orbit of the synchrotron. Spaced around this orbit in twelve equal superperiods are two hundred and forty AG (i.e., alternating gradient) electromagnets weighing 4400 tons, for bending the accelerating beam while focusing it into pencil-thin bundles of particles (hence, "strong-focusing"). Simultaneously, ferrite-loaded dc bias-tuned cavities do the actual beam accelerating at the twelve stations (C), Figure 2, with high-level rf power controlled by proton beam commands. Each station gives the beam an 8000-volt "kick" every revolution, making the energy gain for each orbital turn 96,000 electron volts.

In a 1.1-second magnet excitation-beam acceleration cycle, the particles make more than 340,000 revolutions (over 170,000 miles) synchronized with the rising magnet field and with the phase of the rf voltage waveform. Internal targets may be pushed into the beam's path, or the beam may be deflected out to the target building and experimental areas (D), or both. Figure 5 is a photograph of a typical nuclear event occurring in an external hydrogen bubble

33 Bev
Protons
About ½ mile in a tunnel 18-foot-square cross-section
20 pulses per minute
Cold discharge in hydrogen atmosphere
750-Kev Cockcroft-Walton generator
110-foot-long 50-Mev linear accelerator
240 units each weighing about 20 tons, maximum corrected field 13,000 gauss
12 phase 36,000 kva alternator dc to magnets 6000 volts, and current rising from 0 to 6500 amps, in 1.1 seconds
0.078" thick, oval shape 3¼" vertical axis, 7" horizontal axis
Dry type evaporated titanium gettering. Linac tanks $1X10^{-6}$ mm of hg. synchrotron chamber $3X10^{-6}$mm of hg.
12 power amplifiers rated at 20 kilowatts, output rf power frequency range 1.4 to 4.5 megacycles
100 ft. wide x 250 ft. long
30,000 sq. ft.
60,000 sq. ft.
14,000 tons of concrete
Over 2,000,000 linear ft.

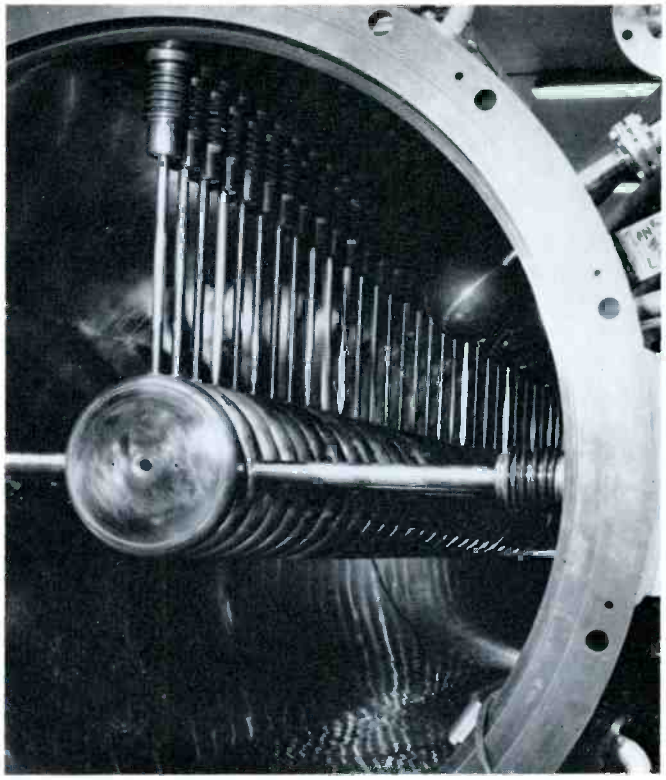


Figure 4 — Linac tank, viewed from low-energy end.

chamber.

During the following two seconds the stored magnetic energy (14 million joules) is returned to the 47-ton flywheel of a 5500-horsepower motor generator for re-use in the next magnet excitation cycle.

AGS Beam Dynamics[2]

In conventional circular magnetic accelerators, the particles are confined to their equilibrium orbits by magnetic focusing forces obtained by shaping the radial magnetic field so that

$$0 < n < 1, \qquad (1)$$

in which n, the field gradient index, is defined by

$$n = -\frac{r}{B}\frac{\partial B}{\partial r}, \qquad (2)$$

where B is the induction and r is the orbit radius. Increasing n strengthens vertical focusing forces at the expense of the radial ones; decreasing n has the opposite effect. The narrow range of n limits the strength of both focusing forces.

Except for necessary straight sections (i.e., field-free sections), n has always been kept constant with azimuth and

[2]J. P. Blewett, "The Proton Synchrotron," Reports on Progress in Physics, Volume XIX (1956) pp. 37-79.

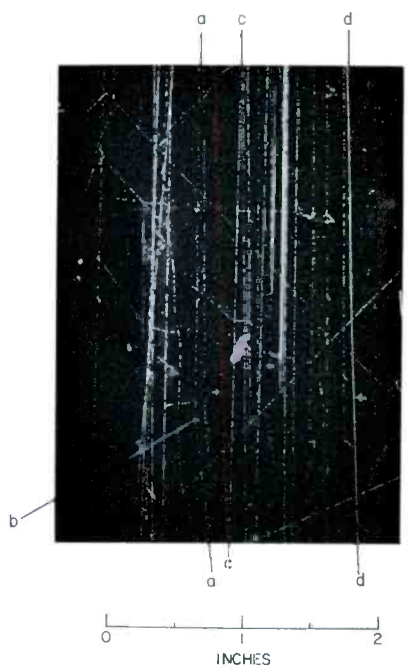


*Figure 5 — Typical nuclear event in hydrogen bubble chamber.

*Photograph showing 630 Mev/c $\pi+$ and protons. The track aa is a $\pi+$ that is scattered with recoil proton b. Track cc shows a beam proton, while dd is a dense background track. About half the length of the chamber is shown. The direction of the beam is from top to bottom of the picture.

relatively large magnets have had to be employed:

Machine	*Location*	*Energy*	*Magnet Weight*
Cosmotron	Brookhaven	3 Bev	2,200 tons
Bevatron	Berkeley	6 Bev	10,000 tons
Synchrophasotron	Dubna	10 Bev	36,000 tons

A conventional (i.e., "weak focusing") 33-Bev proton syncrotron would require more than 200,000 tons of magnet steel.

In the AGS, successive application of very strong magnetic focusing and defocusing forces of equal magnitude results in strong net focusing, reducing the orbit aperture requirement to 2¾″ height by 6″ width compared with the Cosmotron's 7″ by 36″. A slender magnet array is achieved weighing only 4400 tons. This great reduction is explained from the Hill's equations for "betatron" oscillations in circular machines:

$$\frac{d^2r}{dt^2} + (1 - n)\omega_0^2 r = 0, \quad f_r = (1 - n)^{1/2}\frac{\omega_0}{2\pi}; \quad (3)$$

$$\frac{d^2z}{dt^2} + n\omega_0^2 z = 0, \quad f_z = (n)^{1/2}\frac{\omega_0}{2\pi}. \quad (4)$$

ω_0 is the protons' revolution frequency, and as long as $o < n < 1$, f_r and f_z describe particle-orbit, or betatron, oscillations of the order of half the revolution frequency. In the AGS, however, $n \approx \pm 365$, and the betatron oscillation frequency becomes

$$v = \frac{N\mu}{2\pi} = 8.75 \text{ oscillations per revolution.} \quad (5)$$

N is the total number of periods of the alternating gradient system of the magnet ring, sixty in all, and μ represents the oscillatory phase shift through one such pair of focusing-defocusing elements, being defined for stability of oscillation by

$$-1 < \cos\mu < 1 \quad . \quad (6)$$

Since excursions from the equilibrium orbit for a given initial error in particle direction will be proportional to betatron wavelength (i.e., inversely proportional to betatron oscillation frequency), the effective restoring forces in the AGS are an order of magnitude greater than in a weak-focusing machine.

This economy in size and weight is achieved only at the cost of highly precise shaping and positioning of the individual magnets. The net focusing effect, while strong, is not nearly as strong as the individual forces which follow one another in opposing senses. Therefore, small misalignments of individual magnets cause large orbit deviations, particularly for integral numbers of betatron oscillations per revolution. Sensitivity to such misalignments is reduced, however, by decreasing n and the number of betatron wavelengths per revolution; accordingly, the AGS has been designed finally for $v = 8.75$, with alignment of magnet units held to better than half a millimeter.

The integral (i.e., resonant) n values must be avoided. These are conveniently displayed on a stability diagram, Figure 6. Operation is possible only within a small diamond-shaped area between resonances, and further restrictions of operating area arise from subsidiary resonances.

The injected particles vary among each other not only in direction but also in energy, and therefore in momentum and speed, giving rise to radial "synchrotron" oscillations in addition to the betatron oscillations. A proton injected with a momentum error $\Delta\rho$ must travel on a different orbit having a new radius r deviating from the equilibrium radius R by an amount Δr. In a weak-focusing synchrotron these quantities are related by the expression

$$\frac{\Delta\rho}{\rho} = (1 - n)\frac{\Delta r}{R} \quad , \quad (7)$$

defining the limits of a stable, weakly damped sinusoidal oscillation in phase of the beam with respect to the equilibrium phase of the rf accelerating voltage wave of roughly a thousand cycles per second, evidenced by a radial oscillation of several inches amplitude about this new orbit.

In the AGS, however, a proton injected with a momentum error $\Delta\rho$ travels in an alternation of sinusoidal and hyperbolic-functional deviations from a new average circular orbit differing by Δr from the equilibrium orbit in accordance with

$$\frac{v^2\Delta r}{R} = \frac{\Delta\rho}{\rho} \quad . \quad (8)$$

These oscillations are strongly damped with increasing field, and at injection will be of the order of a centimeter in amplitude. They account for the greater width than height of the AGS orbit chamber.

When the mean proton kinetic energy in a bunch is below 7.2 Bev, protons of somewhat larger than mean energy will tend to arrive sooner at the accelerating gaps because their flight time around the ring is smaller. If the rf accelerating voltage waveform is phased so that the accelerating potential across the gap is rising at each passage of the bunch, higher energy particles, arriving early, will collect a smaller energy increment from the gap than lower energy particles arriving later. This illustrates the phase-stability principle. Our word "Synchrotron" and the Russian "Synchrophasotron" arise from this fundamental requirement for capture and acceleration of particles.

Above 7.2 Bev, the particle speeds are already over 99 percent of the velocity of light, and cannot increase much more. Protons having more than the mean energy in the bunch now tend to take longer revolution times because their equilibrium orbit radius is larger than the mean for the bunch. They arrive later at the gaps and must therefore be subjected to a falling accelerating potential in order to receive smaller energy increments than the mean particle. In the AGS, this 7.2 Bev phase transition is passed without

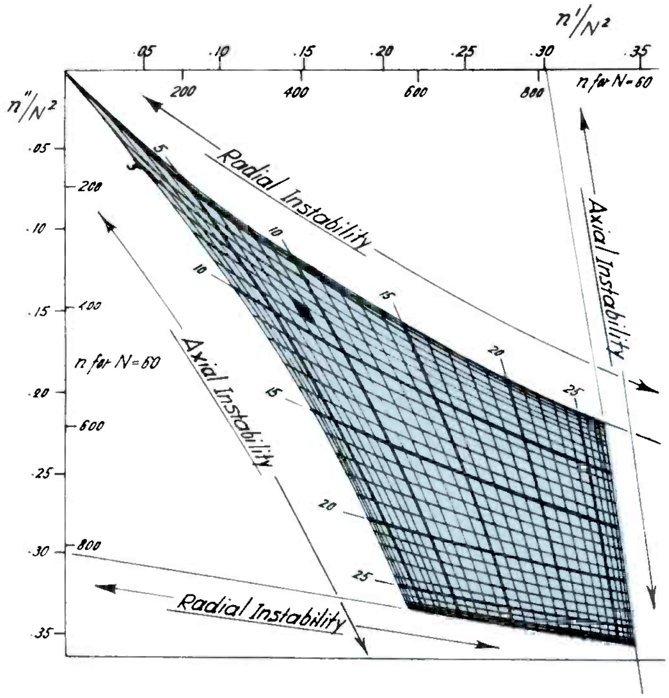


Figure 6 — Stability diagram for the AGS.

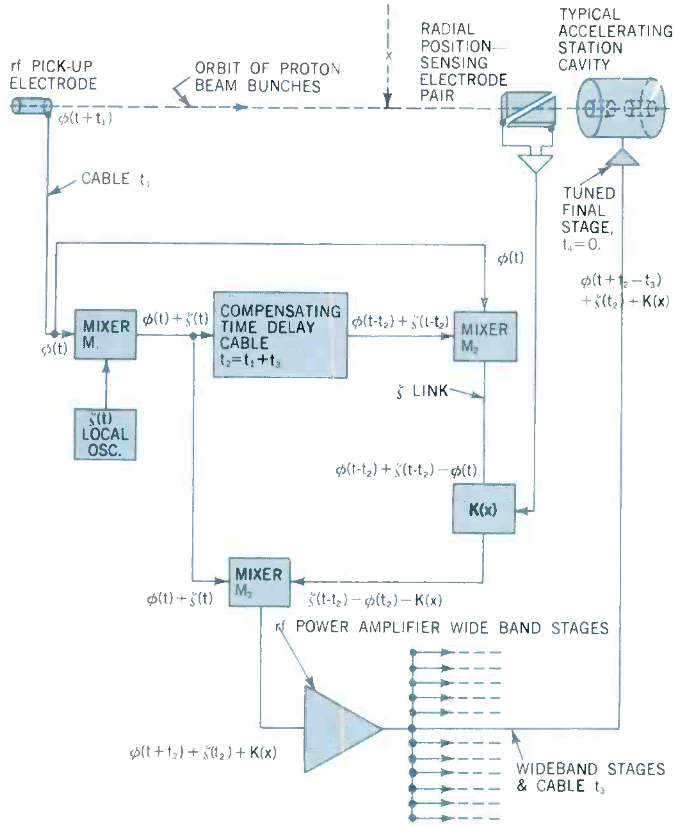


Figure 7 — Principle of phase lock rf acceleration.

generating radial excursions of the proton beam greater than those experienced earlier in the accelerating cycle, by inserting a precisely timed 120° phase step in the rf accelerating voltage waveform.

Phase Lock RF Acceleration[3]

It would not have been possible with conventional frequency programming to accelerate protons in the AGS and retain them within the narrow orbital restrictions of Figure 6, nor to negotiate their phase transition. Therefore a closed loop phase lock rf accelerating system has been developed whose source of commands is the protons themselves. A multiple heterodyning circuit locks the accelerating stations, rf pick-up electrodes, and circulating proton bunches into precise phase relation with each other, effectively eliminating losses of particles to the orbit chamber walls during acceleration.

With twelve identical segments or "superperiods" around the AGS orbit, it becomes convenient to employ twelve accelerating stations spaced at in-phase or out-of-phase orbital positions relative to each other. The twelfth harmonic of the proton revolution frequency is made the accelerating frequency, and a starting oscillator generating its initial value separates the injected Linac beam into twelve bunches of protons spaced equally around the ring. The starting oscillator is then disconnected until the next injection takes place.

A continuous command rf accelerating voltage of frequency ø is induced upon the rf pick-up electrode, Figure 7, by the passing proton bunches[4]. It propagates in a small time interval t_1 to mixer M_1. By this time the continuing voltage at the rf pick-up electrode will have accumulated ϕ (t_1) radians of phase, while M_1 will have accumulated none. After the next interval t, the rf pick-up electrode will have accumulated ϕ $(t + t_1)$ radians, while M_1 will have acquired ϕ (t). Summation of ϕ (t) in mixer M_1 with ζ (t) from a local constant-frequency (i.e., ζ) oscillator will have produced ϕ (t) $+$ ζ (t) radians at the input to the compensating time delay cable t_2, and also at M_3. Simultaneously, the output voltage from t_2 will have accumulated ϕ $(t\text{-}t_2)$ $+$ ζ $(t\text{-}t_2)$ radians at M_2.

Subtractive mixing with ϕ (t) in M_2 provides a constant (i.e., ζ) frequency link for injecting radial phase-correcting beam commands K (x) into the control loop, as well as the 120° phase-transition step and a vernier adjustment, which are not shown in Figure 7. Subtractive mixing in M_3 produces a phase accumulation ϕ $(t + t_2)$ $+$ ζ (t_2) $+$ K (x) radians at the input to the high power wide band rf amplifier, by the end of t.

Time interval t_3 is made the same from M_3 to each ac-

[3]M. Plotkin, "The Radio Frequency Accelerating System for the Brookhaven Alternating Gradient Synchrotron," I.R.E. 1960 International Convention Record, Part 9.

[4]H. S. Snyder, Private communication.

celerating station by cutting all the high power rf transmission cables to the same electrical length. Therefore all stations will have accumulated $\phi\ (t + t_2 - t_3) + \zeta\ (t_2) + K\ (x)$ radians by the end of t, and the difference in phase at that instant between the rf pick-up electrode and the accelerating stations will be

$$\phi\ (t + t_1) - \phi\ (t + t_2 - t_3) - \zeta\ (t_2) - K\ (x) = \phi\ (t_1 - t_2 + t_3) - \zeta\ (t_2) - K\ (x) \text{ radians.} \qquad (9)$$

If the length of the compensating cable is made such that $t_2 = t_1 + t_3$, then the residual phase difference, $-\zeta\ (t_2) - K\ (x)$, will remain constant throughout the interval t. This is the desired result.

So far, all time intervals have been assumed small enough to permit regarding ø as constant. For larger time intervals, ø and its derivatives will be assumed continuous throughout the accelerating cycle, enabling expansion of (9) by Taylor's Theorem:

$$\sum_0^t \phi_{(t)}(\Delta t) = -\zeta(t_2) - K(x) + \frac{d\phi}{dt}(t_1 - t_2 + t_3) + \frac{d^2\phi}{dt^2}\frac{(t_1 - t_2 + t_3)^2}{2!} + \cdots \qquad (10)$$

For $t_2 = t_1 + t_3$, all the derivative terms vanish, and the previous conclusion is again reached, namely,

$$\sum_0^t \phi_{(t)}(\Delta t) = -\zeta(t_2) - K(x). \qquad (11)$$

In the foregoing discussion, propagation times are assumed either frequency-invariant or negligibly small. Expressed in another way, the phase-frequency response of each circuit component must be linear. Otherwise, the beam of protons will make undesirable radial phase-correcting movements.

AGS RF Power Amplifier[5,6]

At 96,000 volts per turn, about 250 kilowatts of rf power must be dissipated in the accelerating station cavities. The rf voltage wave at each one has to be locked in phase, or out of phase as the case may be, with its neighbors; its phase-frequency relation to mixer M_3 must be made essentially linear, and it must faithfully reproduce the M_3 voltage waveform. A linear amplitude transfer is requisite, while injected phase noise, ripple, harmonics, and parasitics must be suppressed. These are performance requirements for the AGS rf power amplifier.

Physically, the amplifier is a 70 db-power gain, 80 kw-output driver unit of nine ferrite-coupled balanced wideband stages, Figure 8, energizing tuned remote final stages at the accelerating stations. The 1.4 to 4.5 mc swept rf command wave arriving from M_3 is amplified to 80 kw, then transmitted over identical coaxial cable pairs to the tuned accelerating stations, Figure 9. The wideband circuit diagram and a typical ferrite inter-stage autotransformer are shown in Figures 10 and 11. The high-level ML-6424 and ML-6696 stages are seen in Figures 12 and 13.

In these high-level stages, large zero-biased Class-A cathode-driven coaxial power triodes are coupled through centertapped step-down autotransformers, Figure 11, closely wound on large Ferroxcube 4-H toroidal cores. At lower levels, grid-driven Class-A tetrodes and pentodes are employed in similar circuits. With the triodes, no broadbanding resistors are needed because their cathode drive input impedance is self loading, the power reappearing usefully on the output side. Neutralization is unnecessary because of the excellent input-output isolation at each stage. A common 4.4 kv 220 adc plate power supply serves both the high-level wideband stages and the tuned remote final stages. The voltage transfer function for the tetrode stage network is [7] The corresponding Class A tetrode wideband transformer stage network is shown in Figure 14. In equation (12) it is assumed that the tetrode dynamic plate resistance is large enough to have negligible effect upon the voltage transfer function.

Equation (12) top next page.[8]

Figure 15 is the Class-A triode wide band transformer stage

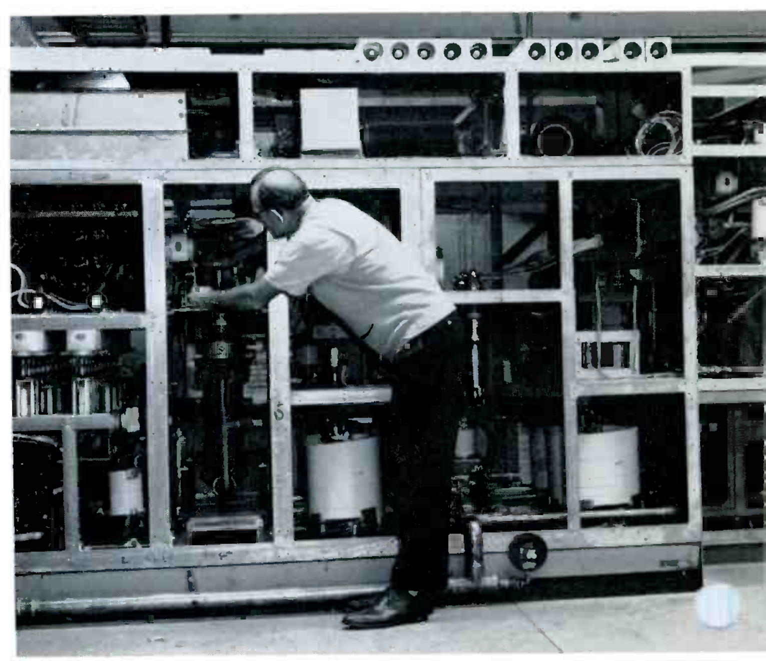
[5]Brookhaven National Laboratory Patent Application S-21074, January 3, 1961, "Amplifier Apparatus for High Energy Particle Accelerator," R. H. Rhéaume, F. Janik, R. E. Zider.

[6]Brookhaven National Laboratory ADD Internal Report RHR-5, March 6, 1959, "A Parallel-Transistor Cascaded Amplifier for Controlling Very Large Currents," R. H. Rhéaume.

[7]Appendix.

[8]Equations (12) and (13) are in form $X = \frac{U}{(V)\ (W)\ (Y)\ (Z)}$

Figure 8 — Rf high power wide-band driver amplifier stages.



$$\frac{e_0 N}{e_g} = \frac{\left(g_m N\right)\left(\frac{C_2}{C_1C_2 + C_1C_3 + C_2C_3}\right)\left(s\right)\left(s + \frac{j}{L_2C_2}\right)\left(s - \frac{j}{L_2C_2}\right)}{\left[s + \frac{1}{2R(C_1 + C_3)} + \frac{j}{\sqrt{L_1(C_1 + C_3)}}\right]\left[s + \frac{1}{2R(C_1 + C_3)} - \frac{j}{\sqrt{L_1(C_1 + C_3)}}\right]\left[s + \frac{1}{2R}\left(\frac{C_1 + C_2}{C_1C_2 + C_1C_3 + C_2C_3} - \frac{1}{C_1 + C_3}\right) + \frac{j}{\sqrt{L_2\left(\frac{C_1C_2 + C_1C_3 + C_2C_3}{C_1 + C_3}\right)}}\right]\left[s + \frac{1}{2R}\left(\frac{C_1 + C_2}{C_1C_2 + C_1C_3 + C_2C_3} - \frac{1}{C_1 + C_3}\right) - \frac{j}{\sqrt{L_2\left(\frac{C_1C_2 + C_1C_3 + C_2C_3}{C_1 + C_3}\right)}}\right]}. \quad (12)$$

$$\frac{e_0 N}{e_g} = \frac{\left(\frac{\mu + 1}{R}\right)\left(N\right)\left(\frac{C_2}{C_1C_2 + C_1C_3 + C_2C_3}\right)\left(s\right)\left(s + \frac{j}{\sqrt{L_2C_2}}\right)\left(s - \frac{j}{\sqrt{L_2C_2}}\right)}{\left[s + \frac{1}{R(C_1 + C_3)} + \frac{j}{\sqrt{L_1(C_1 + C_3)}}\right]\left[s + \frac{1}{R(C_1 + C_3)} - \frac{j}{\sqrt{L_1(C_1 + C_3)}}\right]\left[s + \frac{1}{R}\left(\frac{C_2 + C_3}{C_1C_2 + C_1C_3 + C_2C_3} - \frac{1}{C_1 + C_3}\right) + \frac{j}{\sqrt{L_2\left(\frac{C_1C_2 + C_1C_3 + C_2C_3}{C_1 + C_3}\right)}}\right]\left[s + \frac{1}{R}\left(\frac{C_2 + C_3}{C_1C_2 + C_1C_3 + C_2C_3} - \frac{1}{C_1 + C_3}\right) - \frac{j}{\sqrt{L_2\left(\frac{C_1C_2 + C_1C_3 + C_2C_3}{C_1 + C_3}\right)}}\right]}, \quad (13)$$

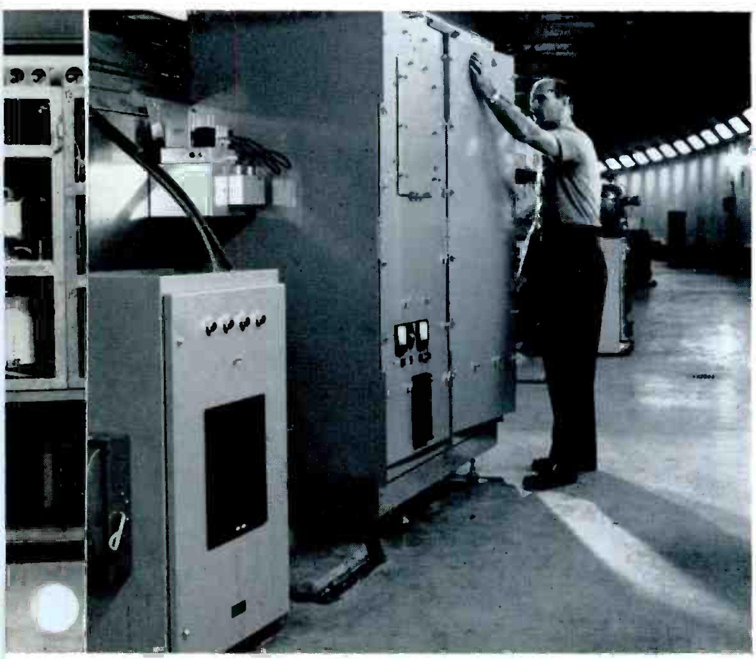
network. The voltage transfer function for this triode stage network is

Equation (13) above.[8]

where $r_p = R$. In equations (12) and (13) it is also assumed that series leakage inductance L_2 is much smaller than primary inductance L_1, that copper and core losses are negligible, and that distributive effects may be disregarded. C_1 and C_3 include terminating capacitances, and C_2 is the parasitic capacitance associated with the series leakage inductance.

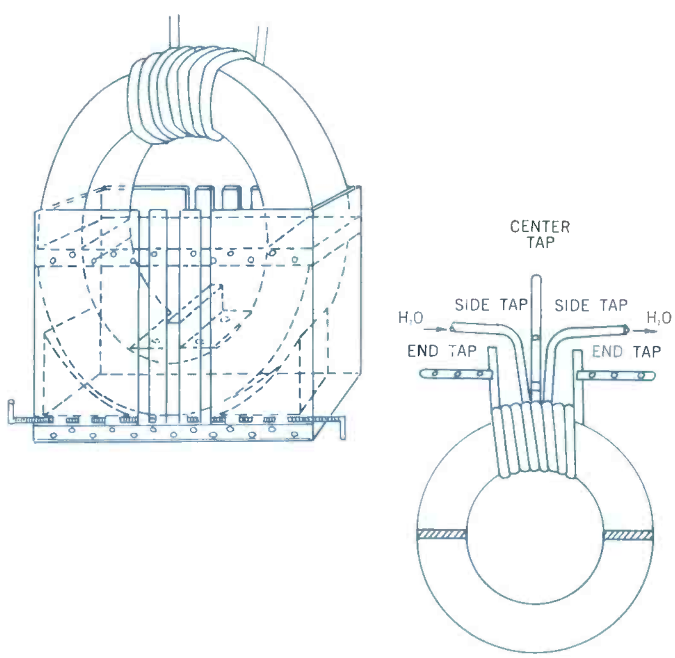
Amplitude-frequency and phase-frequency responses may

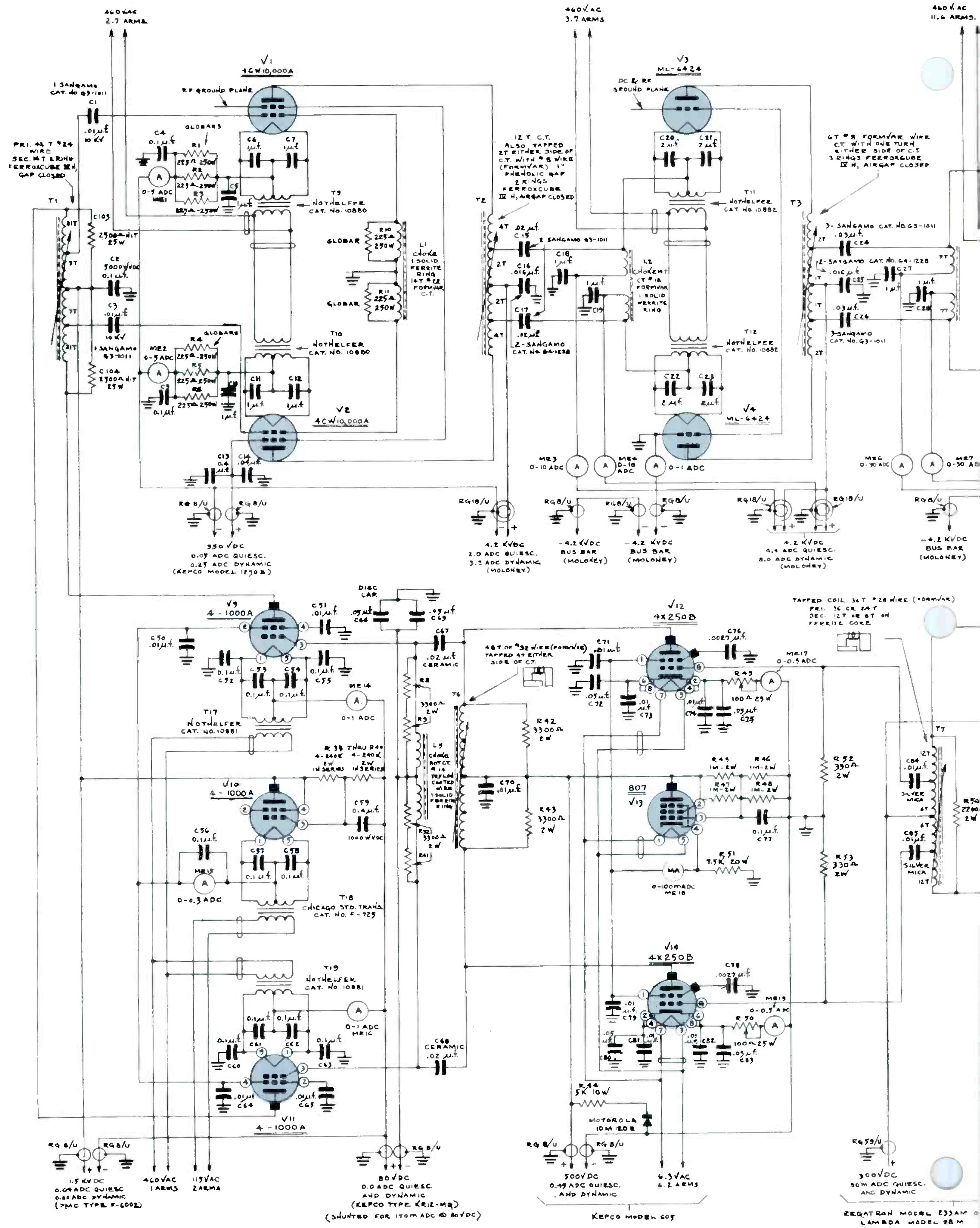
Figure 9 — Typical tuned accelerating station.



Note: Figure 10 — FOLLOWING TWO PAGES.

Figure 11 — Typical ferrite interstage autotransformer.





460 VAC 2.7 ARMS
V1 4CW10,000A
RF GROUND PLANE
GLOBARS
T9 NOTHELFER CAT. NO. 10880
GLOBAR
L1 CHOKE
T10 NOTHELFER CAT. NO. 10880
V2 4CW10,000A
350 VDC 0.05 ADC QUIESC. 0.25 ADC DYNAMIC (KEPCO MODEL 1250B)
460 V AC 3.7 ARMS
V3 ML-6424
DC & RF GROUND PLANE
T11 NOTHELFER CAT. NO. 10882
T12 NOTHELFER CAT. NO. 10882
V4 ML-6424
4.2 KVDC 2.0 ADC QUIESC. 3.2 ADC DYNAMIC (MOLONEY)
-4.2 KVDC BUS BAR (MOLONEY)
-4.2 KVDC BUS BAR (MOLONEY)
4.2 KVDC 4.4 ADC QUIESC. 8.0 ADC DYNAMIC (MOLONEY)
-4.2 KVDC BUS BAR (MOLONEY)
460 V AC 11.6 ARMS
V9 4-1000A
T17 NOTHELFER CAT. NO. 10881
V10 4-1000A
T18 CHICAGO STD. TRANS. CAT. NO. F-725
T19 NOTHELFER CAT. NO. 10881
V11 4-1000A
V12 4X250B
V13 807
V14 4X250B
MOTOROLA 10M120Z
1.5 KVDC 0.64 ADC QUIESC. 0.80 ADC DYNAMIC (PMC TYPE F-6002)
460 VAC 1 ARMS
115 VAC 2 ARMS
80 VDC 0.0 ADC QUIESC. AND DYNAMIC (KEPCO TYPE KR12-MQ) (SHUNTED FOR 170 mA ADC @ 80 VDC)
500 VDC 0.49 ADC QUIESC. AND DYNAMIC
6.3 VAC 6.2 ARMS
KEPCO MODEL 605
300 VDC 30 mA ADC QUIESC. AND DYNAMIC
REGATRON MODEL 233AM OR LAMBDA MODEL 28 M

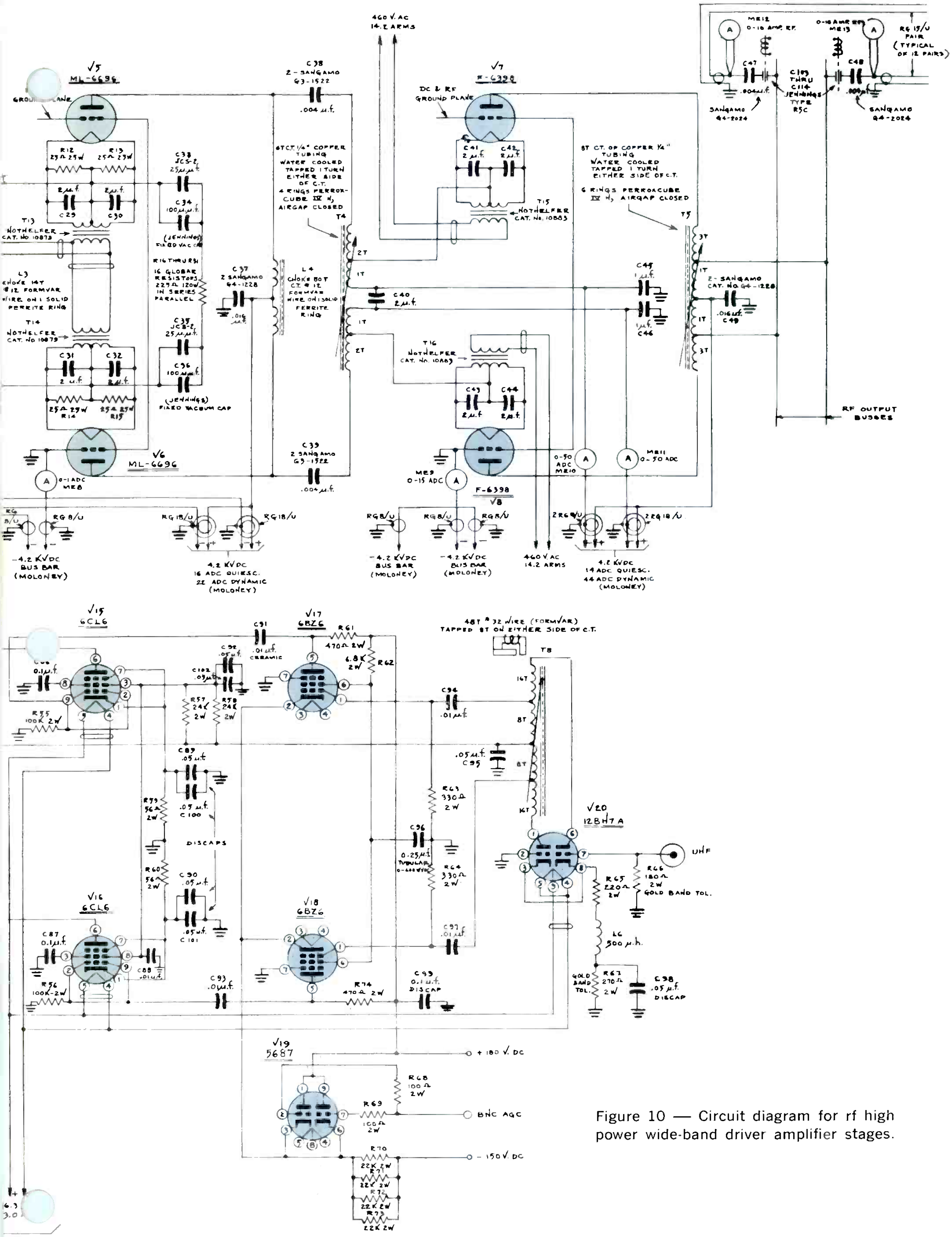


Figure 10 — Circuit diagram for rf high power wide-band driver amplifier stages.

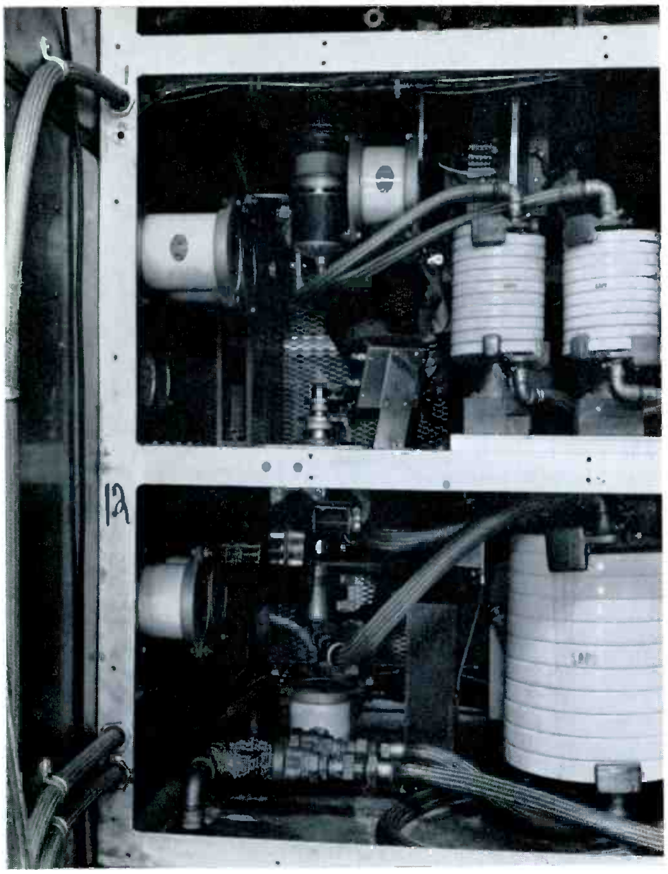


Figure 12 — ML-6424 power triode stage.

Figure 13 — ML-6696 power triode stage.

be determined by substituting real frequency points for s in equations (12) and (13) for realizable sets of circuit parameters. Balanced stages may be analyzed with composite tube characteristics[9,10].

APPENDIX

Derivation of Class-A wide-band transformer networks and transfer functions.

Improved stage gains and smoothness of phase-frequency response may be achieved in wide-band amplifiers for given tube capacitances with certain multipole interstage transfer functions containing finite transfer zeros arising from parasitic capacitances shunting the series inductive elements[11]. However, in high-power wide-band interstage networks the circuit elements must be kept as few as possible to avoid unrealistically high individual element "Q's" and critical adjustments.

[9]Herbert L. Krauss, "Class-A Push-Pull Amplifier Theory," PIRE v 36 n 1 January, 1948, pp. 50-52.

[10]MIT Staff, "Applied Electronics," John Wiley and Sons, N. Y., 1943, pp. 440-446.

[11]B. F. Barton, "Interstage Design with Practical Constraints," *IRE National Convention Record*, 1957, Part 2, pp. 154-159.

Too many elements may cause wide variations of interstage input impedance with frequency, resulting in screen or grid overloading even when the overall stage transfer function is flat. Stability should be such as to ensure constant phase and amplitude responses without trimming during the normal life of the power tubes.

Wide band interstage transformers and autotransformers offer a convenient solution for these requirements. The high-frequency equivalent transformer circuit of Figure 16(d)[12] is a three-pole low-pass filter network. By lumping the external source and load capacitances with $\overline{C}_p$ and $\overline{C}_s$, and by adding the primary shunt inductance and the load resistance at the input and output ports, respectively, the Class-A tetrode wide-band transformer stage network is obtained, Figure 14. Copper and ferrite losses and the tetrode dynamic plate resistance are omitted.

$$Y_1 = sC_1 + \frac{1}{sL_1} = \frac{s^2C_1L_1 + 1}{sL_1}. \qquad (14)$$

[12]T. R. O'Meara, "Analysis and Synthesis with the 'Complete' Equivalent Circuit for the Wide-Band Transformer," 1961 Electronic Components Conference Proceedings, pp. 21-1 through 21-24. See also F. E. Terman, "Radio Engineers' Handbook," McGraw-Hill, N. Y., 1943, p. 370, Figure 12(b).

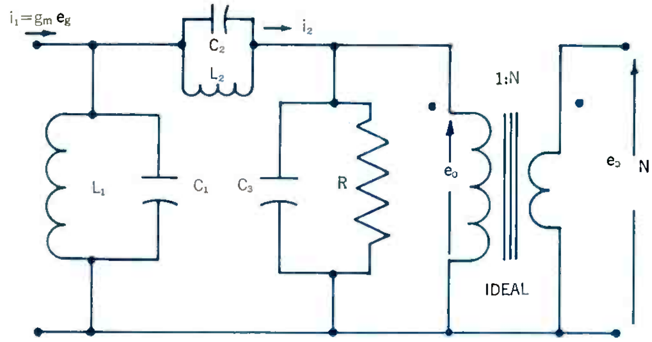


Figure 14 — Class A tetrode wide-band transformer stage network.

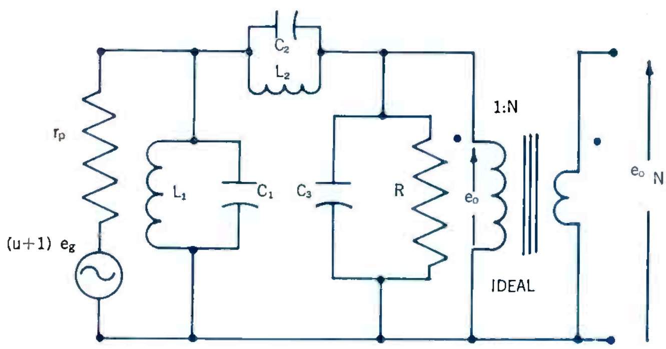


Figure 15 — Class A triode wide-band transformer stage network.

$$Z_1 = \frac{sL_1}{s^2C_1L_1 + 1}. \tag{15}$$

$$Y_2 = sC_2 + \frac{1}{sL_2} = \frac{s^2C_2L_2 + 1}{sL_2}. \tag{16}$$

$$Z_2 = \frac{sL_2}{s^2C_2L_2 + 1}. \tag{17}$$

$$Y_3 = sC_3 + \frac{1}{R} = \frac{sC_3R + 1}{R}. \tag{18}$$

$$Z_3 = \frac{R}{sC_3R + 1}. \tag{19}$$

$$(i_1 - i_2)Z_1 = i_2(Z_2 + Z_3). \tag{20}$$

$$i_1 = \frac{i_2(Z_1 + Z_2 + Z_3)}{Z_1} \tag{21}$$

$$i_2 = \frac{e_0}{Z_3}. \tag{22}$$

(22) into (21):

$$\frac{e_0}{i_1} = \frac{Z_3Z_1}{Z_1 + Z_2 + Z_3}. \tag{23}$$

(15), (17), (19) into (23):

$$\frac{e_0}{i_1} = \frac{\left(\frac{R}{sC_3R + 1}\right)\left(\frac{sL_1}{s^2C_1L_1 + 1}\right)}{\frac{sL_1}{s^2C_1L_1 + 1} + \frac{sL_2}{s^2C_2L_2 + 1} + \frac{R}{sC_3R + 1}}. \tag{24}$$

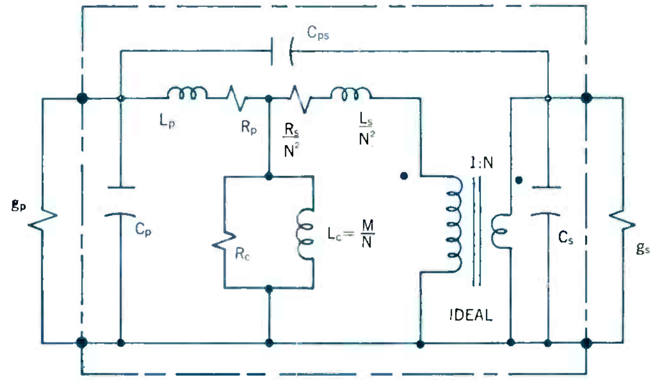


Figure 16A — "Complete" equivalent circuit for a wide-band or pulse transformer.

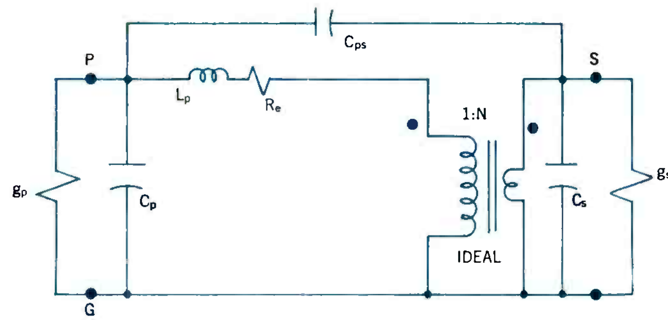


Figure 16B — Simplified low-pass filter equivalent circuit, valid for high frequencies.

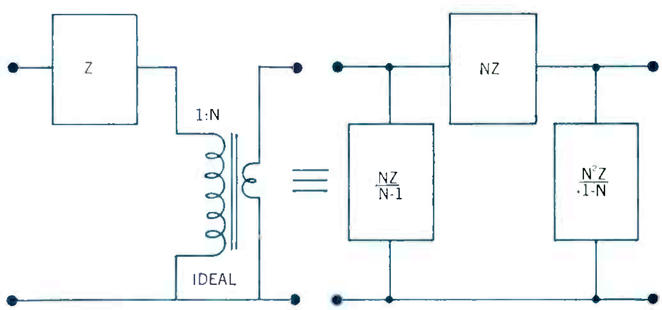


Figure 16C — Network transformation useful in deriving equivalent circuits for a transformer, valid for high fequencies.

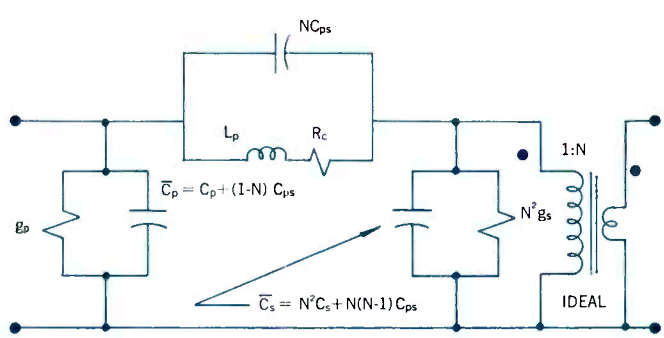


Figure 16D — Transformed equivalent circuit for a transformer, valid for high frequencies, identical to that in Figure 16B.

After expanding, regrouping, and making the assumption $L_1 >> L_2$, (24) becomes:

$$\frac{e_0}{i_1} = \frac{\left(\frac{C_2}{C_1C_2 + C_1C_3 + C_2C_3}\right)(s)\left(s^2 + \frac{1}{C_2L_2}\right)}{\left[s^4 + \frac{s^3(C_1 + C_2)}{R(C_1C_2 + C_1C_3 + C_2C_3)} + \frac{s^2(C_1 + C_3)}{L_2(C_1C_2 + C_1C_3 + C_2C_3)} + \frac{s}{L_2R(C_1C_2 + C_1C_3 + C_2C_3)} + \frac{1}{L_1L_2(C_1C_2 + C_1C_3 + C_2C_3)}\right]}. \qquad (25)$$

The denominator of (25) will be factored by Lin's[13] method. It takes the form:

$$s^4 + B_3s^3 + B_2s^2 + B_1s + B_0 = 0. \qquad (26)$$

A trial divisor is formed from the last three terms of (26);

$$s^2 + \frac{B_1}{B_2}s + \frac{B_0}{B_2}, \qquad (27)$$

where $$B_0 = \frac{1}{L_1L_2(C_1C_2 + C_1C_3 + C_2C_3)}, \qquad (28)$$

$$B_1 = \frac{1}{L_2R(C_1C_2 + C_1C_3 + C_2C_3)}, \qquad (29)$$

$$B_2 = \frac{C_1 + C_3}{L_2(C_1C_2 + C_1C_3 + C_2C_3)}. \qquad (30)$$

Inserting (28), (29), (30) in (27) and simplifying, the trial divisor becomes

$$s^2 + \frac{s}{R(C_1 + C_3)} + \frac{1}{L_1(C_1 + C_3)}. \qquad (31)$$

Dividing (31) into the denominator of (25) and neglecting the small remainder, the resulting dividend is:

$$s^2 + \frac{s}{R}\left[\frac{C_1 + C_2}{C_1C_2 + C_1C_3 + C_2C_3} - \frac{1}{C_1 + C_3}\right] + \left[\frac{C_1 + C_3}{L_2(C_1C_2 + C_1C_3 + C_2C_3)} - \frac{1}{L_1(C_1 + C_3)} - \frac{C_1 + C_2}{(C_1C_2 + C_1C_3 + C_2C_3)(C_1 + C_3)R^2} + \frac{1}{(C_1 + C_3)^2(R^2)}\right]. \qquad (32)$$

For the range of component magnitudes of practical interest, (32) may be further simplified:

$$s^2 + \frac{s}{R}\left[\frac{C_1 + C_2}{C_1C_2 + C_1C_3 + C_2C_3} - \frac{1}{C_1 + C_3}\right] + \left[\frac{C_1 + C_3}{L_2(C_1C_2 + C_1C_3 + C_2C_3)}\right]. \qquad (33)$$

Expressions (31) and (33) may now be factored by the quadratic formula, taking advantage in each case of the relatively small magnitude of the coefficient of s for simplifying the portion under the radical sign:

$$s_{p1}, s_{p1}^* = -\frac{1}{2R(C_1 + C_3)} \pm j\sqrt{\frac{1}{L_1(C_1 + C_3)}}, \qquad (34)$$

$$s_{p2}, s_{p2}^* = -\frac{1}{2R}\left(\frac{C_1 + C_2}{C_1C_2 + C_1C_3 + C_2C_3} - \frac{1}{C_1 + C_3}\right) \pm j\sqrt{\frac{1}{L_2\frac{(C_1C_2 + C_1C_3 + C_2C_3)}{(C_1 + C_3)}}}. \qquad (35)$$

[13]Shih-Nge Lin, "Methods of Successive Approximations of Evaluating the Real and Complex Roots of Cubic and Higher Order Equations." *J. Math. Phys.*, Vol. 20, No. 3, August 1941.
V. Del Toro and S. R. Parker, "Principles of Control Systems Engineering," McGraw-Hill, N. Y., 1960, pp. 644-647.

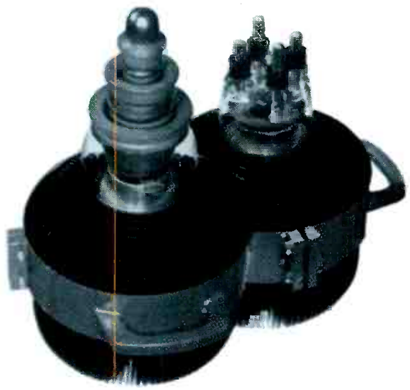
When equations (34) and (35) are substituted in the denominator of (25), and $g_m e_g$ for the driving tetrode is substituted for i_1 in (25), and both sides of (25) are then multiplied by $g_m N$, equation (12) is obtained.

Figure 15 and equation (13) for the Class-A grounded grid triode are derived from the substitution of $(\mu + 1) e_g$ in series with the triode dynamic plate resistance r_p at the input port of Figure 14 in place of $i_1 = g_m e_g$, then assuming that $r_p = R$, the transformed load resistance. The derivation of equation (14) then proceeds in a fashion similar to that for equation (13).

The additional input loading of Class-A_2 grounded grid triode operation has no effect upon equation (13), but does slightly lower the magnitude of the load resistance presented to the previous stage.

Tube Life of ML 6421F vs. ML 5667 at Station WWV

Radio Station WWV, of the National Bureau of Standards, broadcasts continuous standard frequency and time signals on six different frequencies. WWV has been using Machlett ML-6421F triodes as replacements for ML-5667 tubes originally installed in all final audio and radio frequency stages of four high power transmitters, operating at 5, 10, and 15 megacycles, respectively. Tube life data of the newer ML-6421F, which has a thoriated tungsten filament, and ML-5667, which has a pure tungsten filament, has been carefully recorded. The following is a tabulation of this data as of July 17, 1963.



ML-5667 (Pure tungsten filament)

In RF service:	14 tubes; avg. life 16,128 hours per tube
In Mod. service:	9 tubes; avg. life 23,669 hours per tube
In combined service:	23 tubes; avg. life 19,898 hours per tube

ML-6421F (Thoriated tungsten filament)

In RF service:	8 tubes; avg. life 47,134 hours per tube
In Mod. service:	4 tubes; avg. life 55,460 hours per tube
In combined service:	12 tubes; avg. life 49,826 hours per tube

To date, in RF service, thoriated tungsten filament tubes have given almost 3 times the life of pure tungsten tubes; in Modulator service thoriated tungsten tubes have given over twice the life of pure tungsten filament tubes; in combined service the thoriated tungsten filament tubes have given over $2\frac{1}{2}$ times the life of pure tungsten tubes. All 12 original thoriated tungsten tubes are still in operation.

TRANSMITTER FREQUENCY	TUBE TYPE	SERIAL NUMBER	TUBE POSITION	HOURS LIFE AS OF 7-17-63	ORIGINAL INSTALLATION DATE**
5 Mc	ML-6421F	428425	RFL	53,126	5-7-56
	ML-6421F	426798	RFR	53,126	5-7-56
	ML-6421F	425856	ML	58,435	7-13-55
	ML-6421F	425857	MR	58,435	7-13-55
10 Mc	ML-6421F	426800	RFL	50,846	4-5-56
	ML-6421F	428328	RFR	50,846	4-5-56
	ML-6421F	426791	ML	52,486	12-14-55
	ML-6421F	426801	MR	52,486	12-14-55
15 Mc	ML-6421F	428330	RFL	51,167	10-18-56
	ML-6421F	425611	RFR	51,167	10-18-56
	ML-5541	410224	ML	70,072	10-9-53
	ML-5541	410108	MR	70,072	10-9-53

LEGEND: RFL — Radio Frequency, Left; ML — Modulator, Left; RFR — Radio Frequency, Right; MR — Modulator, Right

General Operating Conditions per tube:

	FILAMENT VOLTS*	PLATE VOLTS	PLATE AMPERES
Modulator — 6421	6.0 A.C.	6000 D.C.	0.1
5541	5.3 A.C.	6000 D.C.	0.1
Radio Frequency	6.0 A.C.	6000 D.C.	0.9

Modulators have static current of 0.1 Amperes. They are pulsed with a 5 cycle burst of 1000 cycles once per second, and voice and telegraphic code announcements for approximately 30 seconds out of each 5 minutes.

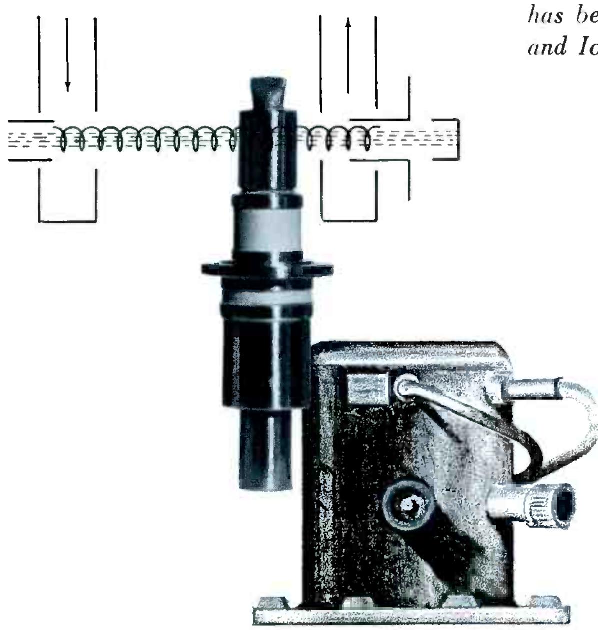
*Filament voltage metered, recorded a minimum of once per day; filaments operate within ±0.1 volt. Care and attention to operation of tubes at WWV are, of course, excellent and contribute to their very substantial life figures.

**There have been no tube failures in this group of thoriated tungsten filament tubes. All tubes are still in operation.

Editor's Note:

The Committee on Thermionics and Ionics has been established by engineering groups from Raytheon Company and its affiliates to provide information of advanced technological interest to the Company. Of the two seminars held in 1963, "Vacuum Technology" and "Tubes in Space," CATHODE PRESS is pleased to print three of the papers given at the latter meeting. "The Impact of Space Environment on Electron Tube Design" by R. C. Hergenrother, Spencer Laboratory; "CW Amplitrons for Space Communications" by W. W. Teich, Spencer Laboratory; and "Negative Grid Tubes for Space Applications" by W. Brunhart, The Machlett Laboratories.

Dr. Peter F. Varadi of The Machlett Laboratories, Inc., has been the Chairman of the Committee on Thermionics and Ionics since its inception.



DR. R. C. HERGENROTHER

Dr. R. C. Hergenrother is Consulting Engineer to Spencer Laboratory on all types of present and forward looking programs. He was appointed to this position in May, 1962.

He received the degree of Bachelor of Arts from Cornell University in 1925. He went to Pennsylvania State College in 1927 as an instructor in physics and received the degree of Master of Science in Physics from that school in 1928. He continued his graduate studies at the California Institute of Technology, where he did research on X-ray crystal structure analysis, and was awarded the degree of Ph.D. cum laude in 1931.

Dr. Hergenrother joined Raytheon in 1945 as a senior engineer, and served as Manager of the Beam Tube Laboratory from 1950-62. Half a dozen patents have been issued and others are pending from his work at Raytheon. He has published articles and presented papers on camera tubes, color television tubes, storage tubes, electron optics, reflex klystrons, magnetic focus backward-wave oscillators, and electrostatic focus backward-wave oscillators.

The Impact of Space Environment on Electron Tube Design

By Dr. R. C. HERGENROTHER, Spencer Laboratory, Raytheon Company

The Evolutionary Process

Electron tubes, as well as other man-made devices, can be thought of as progressing through a process of evolution analogous to that which we see operating in nature. The environment in which the device is fabricated and used has a dominant effect on the form and capabilities of the device.

Earthbound Environment

The evolution of electron tubes started in an earthbound environment which had both advantages and problems. For example, the earth is a virtually infinite thermal sink, so there is no problem for heat dissipation. On the other hand, the atmosphere is a handicap to many fabrication processes such as metallurgy, which becomes a very "dirty" process. The problem of enclosing the electron tube in a gas-tight envelope having electrically insulated leads passing through it and containing windows for rf radiation is sometimes formidable. The problem of exhausting, baking and sealing the envelope require a complex, costly and time consuming technique.

Airborne Environment

When electron tubes became airborne, additional requirements of increased ruggedness and decreased weight were added to those already existing and thermal dissipation became less easy.

Space Environment

The advent of spaceborne vehicles, however, introduced a new environment which differs radically from the terrestial environment. The ultrahigh vacuum, the low temperature, the high energy particle radiation, and the limited thermal capacity of an isolated system, each raises its own problem for the electron tube designer. How some of these problems may be met and others turned to advantage will next be considered.

Primary Requirement for Spaceborne Electronics Reliability

The electronic systems in spaceborne vehicles serve functions of communication, control, and, in some instances, propulsion. The cost of launching a vehicle is very high and once it is spaceborne, it is inaccessible for modification or repair in the usual sense. This places a high premium on reliability of the components comprising such systems.

Efficiency

Another requirement which is second only to reliability is high efficiency. Improvements in efficiency are reflected immediately in decreased power input requirement, and thus, in size and mass of power source and power conversion devices. Another benefit of increased efficiency is a reduction in the thermal dissipation problem, which will be discussed later.

Minimum Mass

Any reduction of mass which may be achieved by improved efficiency or other means exerts a great leverage in that this reduces the power required for launching and the powers required for propulsion.

Electron Tubes versus Solid State Electron Devices

It is important to raise the question regarding which, if any, functions of spaceborne electronic systems are best performed by solid state electron devices and which are best performed by electron tubes.

Solid state devices are compact and have a potential of long life capability. Their power output capability, however, is limited and their frequency-bandwidth capability is also limited. Solid state devices are affected by high energy particle radiation and must be adequately shielded if required to operate in regions of high density, high energy particles, as for example the Van Allen belt. High temperature processing, such as sterilization, can also cause deterioration of some solid state devices.

Electron tubes, on the other hand, can have a high power output capability and also have a wide frequency bandwidth capability. Tubes are virtually unaffected by high energy particle radiation and are not affected by high temperature processing, such as sterilization.

The best engineering trade-off of these characteristics appears to be achieved by using radiation-shielded, solid state electronics at low power levels if the frequency bandwidth requirements are within its capabilities. At power levels above one (1) watt, electron tubes are mandatory. A notable example is the Telstar communication satellite which uses solid state electronics throughout except for the power output tube, which is a traveling wave tube. It will be recalled that the first Telstar had a failure of the solid state electronics because of insufficient shielding.

Properties of Space Environment

The radical properties of the space environment in which spaceborne electronic systems will be required to operate are listed below:

Ultrahigh Vacuum
Low Ambient Effective Temperature
Virtually Zero Acceleration (Force)
High Energy Particle Radiation
Meteoroids
Limited Thermal Capacity (of Vehicle)

Ultrahigh Vacuum Environment

The most favorable factor of space environment for electron tubes is the ultrahigh vacuum. This is spectacular by terrestial standards, as shown in Table I.

TABLE I[1]

Altitude	*Pressure (Torr)*	*Molecules/cm³*
0	760	2.7×10^{19}
100 mi	10^{-6}	3.5×10^{10}
500 mi	10^{-10}	3.5×10^{6}
1000 mi	10^{-12}	3.5×10^{4}
Interplanetary	0.3×10^{-15}	10

At a pressure of one (1) Torr or one (1) millimeter of mercury, a cubic centimeter contains 3.5×10^{16} molecules of gas. The achievement of pressure of 10^{-9} Torr or 3.5×10^{7} molecules per cubic centimeters in sealed off tubes in the earth's environment is technically difficult. This pressure is already reached at an altitude of 300 miles above the earth's surface, and at 1000 miles the gas density is of the order of 3.5×10^{4} molecules per cubic centimeter and is believed to be of the order of 10 molecules per cubic centimeter in interplanetary space.

Insulation

One benefit of a total environment of high vacuum is that this serves as the best possible insulation. This means that insulation needs are reduced to only mechanical support requirements. Limitations on conductor spacings are imposed only by electromechanical forces and by cold emission which can occur at electric fields above 10^{6} volts per centimeter.

Envelopes

The high vacuum existing in space suggests the possibility of constructing the tube envelope so that it can be opened when the system is in space to achieve the benefit of a continuous high speed, ultra high vacuum pumping. Such a procedure would alleviate many common electron tube problems, such as ion oscillation effects, cathode poisoning, and gettering.

A more radical approach which may be considered is the complete elimination of an envelope. This would not only increase the pumping speed but would eliminate the need for leads and rf windows which are required in an envelope. Transmission lines for rf can be reduced or even in principle eliminated if the interaction circuit and radiator could be combined. The elimination of the rf window would eliminate the problems which these windows are subject to, such as losses, mismatch, multi-pactor and breakdown.

Cathodes

The use of an openable envelope would permit the use of any type of conventional cathode which could be processed in the usual way. The elimination of the envelope would introduce new problems with respect to the cathode. It would be possible to defer activation or processing of the cathode until the system is in the space environment, in which event, any type of cathode could be used. This would, however, preclude the possibility of testing the system with the cathode in earth environment before launch. It would be possible to test the system before launch in a bell jar which could be evacuated. The system would then be removed from the bell jar and installed in the vehicle but would not be re-activated until it was in a space environment. This procedure would preclude the use of oxide coated cathodes or similar types, but would permit the use of pure tungsten or tantalum cathodes, dispenser type cathodes, tunnel cathodes and secondary emission cathodes.

Cathode Heating

In addition to the conventional ohmic heating of thermionic cathodes, two other heating methods can be considered. It would be possible, for example, in systems which did not get too far from the sun to use solar energy directly for heating the cathode. This requires focusing the solar image on the cathode and implies orientation requirements. Another interesting approach is to use "collector-cathode" heating. In this scheme, the collector from one tube is combined with the cathode of the following tube so that the energy dissipated at the collector is used to supply the cathode heating energy. Both of these methods, which are illustrated in Figure 1, have the advantage of reducing the energy input requirements.

The ideal cathode for space environment is the tunnel cathode since this does not need to be heated and can theoretically achieve a high level of efficiency.

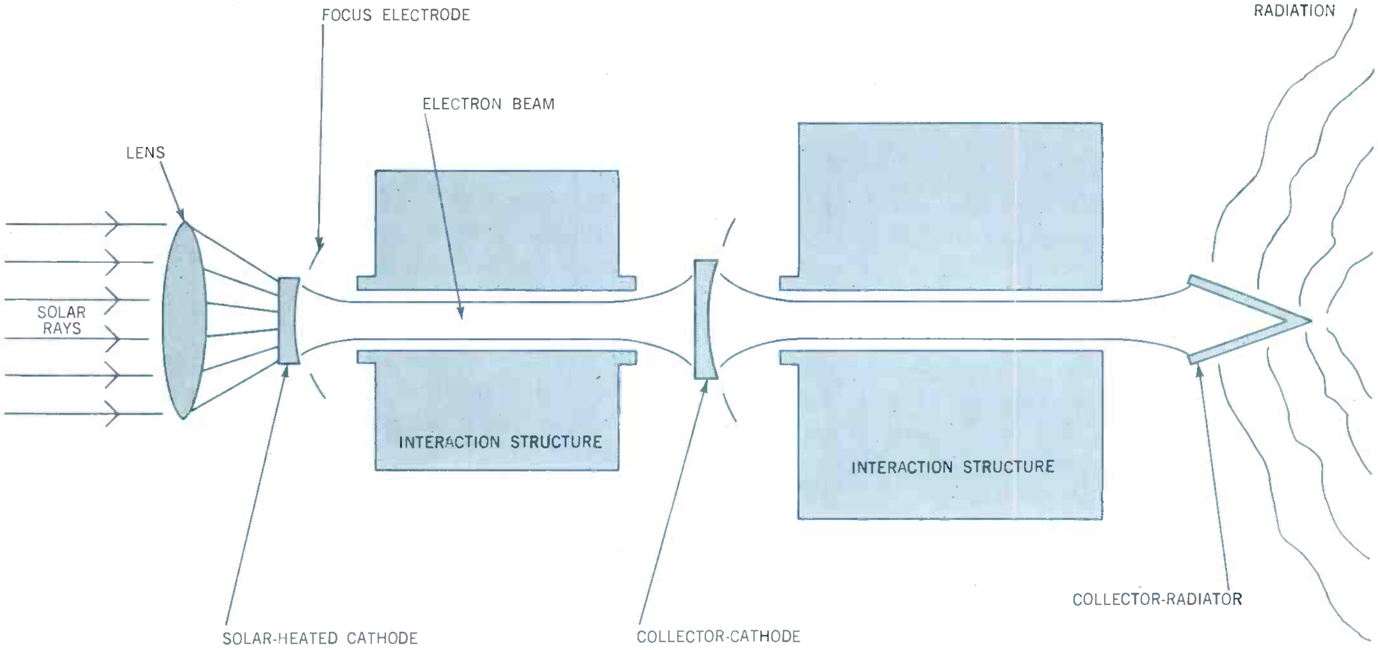


Figure 1 — Methods of Cathode Heating and Spent Electron Beam Power Dissipation.

[1]TABLE I Reference — Jastrow, R. and Kyle, H. The Earth's Atmosphere Sec. 2.1 of Handbook of Astronautical Engineering, First Ed. Heinz Hermann Kelle, ed., McGraw-Hill Book Co., Inc., 1961, pp. 2-2 – 2-13.

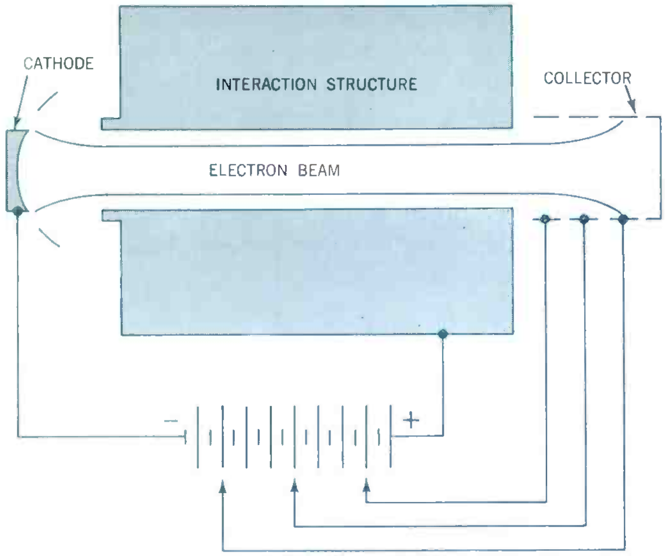


Figure 2 — Retarded Potential Collector.

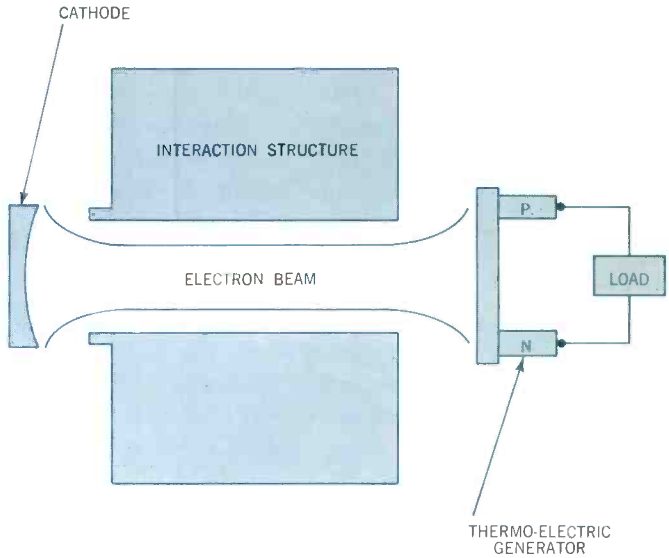


Figure 3 — Conservation of Spent Electron Beam Power.

Beam Energy Conservation

To improve the efficiency of the tube and at the same time minimize the problem of heat dissipation, maximum use should be made of the retarded voltage beam collector concept, which is shown schematically in Figure 2.

Another method of conserving energy would be to combine the target electrode with a thermoelectric generator, as indicated in Figure 3.

Beam Energy Dissipation

It might be supposed that the energy of the used electron beam could easily be disposed of by letting the electron beam be projected into free space. Such a procedure would, however, result in the build-up of a positive electric potential on the surface of the vehicle and the resultant electric field would quickly reach sufficient strength to pull the electrons back to the surface of the vehicle which would then act as a collector, as shown in Figure 4. The space charge cloud, which would build up around the vehicle, could conceivably interfere with radio communication.

The only way to get rid of residual waste thermal energy in the space vehicle is through radiation. The thermal power radiated from a surface depends on its emissivity and is proportional to the area and to the absolute temperature with exponent four. This means that doubling the temperature is equivalent to a sixteen fold increase in area. This suggests the use of a small target of tungsten, or the like, heated by the waste electron beam to a very high temperature and located in the shadow of the vehicle, as is indicated in Figure 1.

Magnetic Field Effects

Magnetic fields in interplanetary space are extremely weak being two or three orders of magnitude lower than the earth's magnetic field. These fields then will exert no action on the electron tubes. However, any magnetic fields in the vehicle produced by focusing systems, for example, will be acted on by the earth's magnetic field when the vehicle is in the vicinity of the earth and produce a mechanical couple such as is produced on a compass needle by the earth's field. To minimize this effect, magnetic moments within the vehicle should be balanced so their vector sum is virtually zero. Periodic magnetic focus systems should have an even number of magnets, for example. Conversely, the earth's magnetic field could be used for orientation maneuvers by using solenoids through which controlled electric currents can be sent.

Meteoroids

The density of meteoroids in space is very low[2] and is in inverse proportion to their size. Meteoroids of 1 (one) microgram mass have an incidence of about 3 (three) particles per square meter per year, and particles of 1 (one) milligram mass have an incidence of 1 (one) particle per square meter per 300 years. Shielding would not be necessary since a 1 (one) microgram particle would have a negligible effect even if it struck the cathode and even a 1 (one) milligram particle would have only a minor effect.

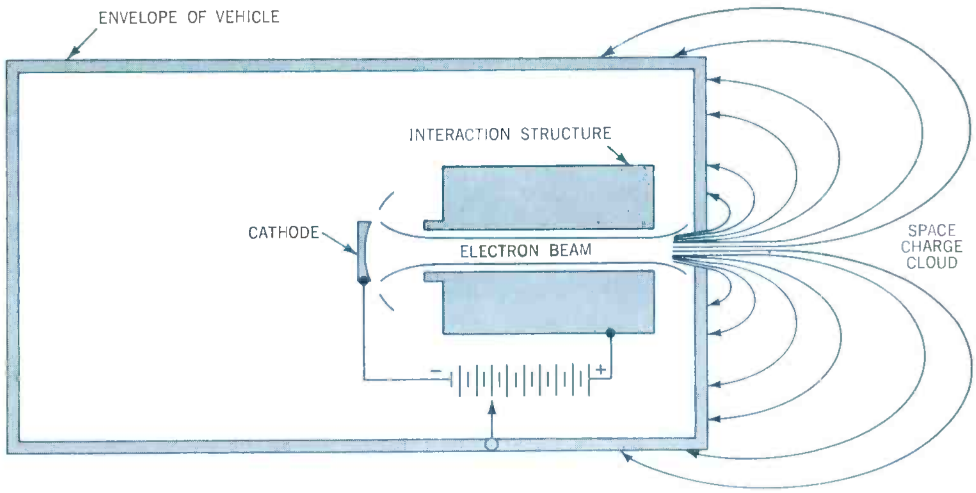


Figure 4 — Spent Electron Beam Projected into Space. (Note: If Envelope is at Cathode Potential, Electron will not penetrate Envelope Opening).

Particle Radiation

Particle radiation from cosmic rays comprises high energy protons, alpha particles and completely stripped nuclei with masses up to ten. The overall average in free space is of the order of 2.5 particles per cm^2 per sec.

Solar flares give rise to particles with energies ranging from a fraction of BEV up to 20 BEV. These occurrences are related to solar flares and the solar cycle which are not closely predictable. The most intense radiation is in the Van Allen belt comprising protons and electrons trapped in the earth's magnetic field, and in an artificial electron belt produced by a high altitude nuclear explosion of July 9, 1962 which is similarly trapped by the earth's magnetic field.

These particle radiations, particularly solar flares and trapped radiation, can have serious biological effects and are being intensively studied for this reason. The effects on solid state devices, such as transistors and solar cells, are significant and are being studied[3]. The effects of these particles on electron tubes would be confined to their effects on insulators and these are expected to be orders of magnitude less than the effects on semiconductors. No shielding or other electron tube design considerations will be affected by these particle radiations as far as we know at present.

Summary

In the space environment, reliability is of vital importance and is the basic factor guiding the design and construction of electronic systems. The techniques of quality control and testing must be carried to the highest level of refinement.

Second only to reliability is the requirement for high overall efficiency. This factor increases in importance with increasing power levels. Solid state electronic devices have the advantage of compactness and ruggedness. They have high reliability and long life when adequately shielded from high energy particle radiation. They are a natural choice where their frequency and bandwidth capabilities and their power handling capabilities are adequate for the required application.

At power levels above one watt, solid state microwave devices reach their present state-of-the-art limit of power output, and at higher power levels, tubes are used.

In the range of one (1) watt to 100 watts the sealed-off tube represents the simplest solution. As power is increased, it becomes more desirable to open up the envelope to outside space after the system has gone beyond the earth's atmosphere. This requires the development of simple, reliable, light-weight, one-shot vacuum tight devices. At sufficiently high power levels, the envelope-less structure with its freedom from lead through and rf windows with its simplified transmission lines becomes attractive to the designer.

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[2]Alexander, W. M., McCracken, C. W., Secretan, L. and Berg, O. E. Review of Direct Measurements of Interplanetary Dust From Satellites and Probes X-613-62-25, Goddard Space Flight Center, NASA, 1962.

[3]Hulten, W. C., Honaker, W. C., and Patterson, John L.: Irradiation Effects of 22 and 240 Mev Protons on Several Transistors and Solar Cells NASA TN D-718, 1961.

WESLEY W. TEICH

Mr. Wesley W. Teich is a Principal Engineer in the High Power Tube Laboratory of the Raytheon Microwave and Power Tube Division. He has been active in the development of microwave tubes since joining the company in 1945, and is currently directing activity in the development of low power Amplitrons and Stabilotrons for several communications and telemetry applications.

Mr. Teich received his B.S. degree in electrical engineering from Iowa State University, Ames, Iowa, in 1945. He has since completed graduate courses in this field at the Massachusetts Institute of Technology.

He has served as a member of the IRE standards committee on operating measurements of microwave oscillators and more recently, as a member of the Technical committee on Electron Tubes.

Design of CW Amplitrons for Space Applications

By WESLEY W. TEICH, High Power Tube Laboratory, Raytheon Microwave and Power Tube Division, Burlington, Massachusetts

The requirements for microwave transmitters to be carried into space place unusual demands on the microwave tubes to be employed. To best meet these demands, not only must careful attention be paid to the design details of the device selected, but also it is important that selection of the basic device to be employed be based on proper consideration of the needs of the application.

The basic simplicity and high efficiency of the Amplitron make the device attractive for space applications. The required rf structures lend themselves well to conduction cooling at ground potential and to low mass and high rigidity which promise high resistance to modulation or damage from severe shock and vibration. The high efficiency, of course, is reflected in low power consumption and, consequently, in minimum size and weight of the associated power supply.

Table I presents the characteristics of four Amplitrons currently being built at Spencer Laboratory for several space applications. The anode structures of these four tubes are nearly identical, but variations in the packaging arrangement and the selected operating point adapt them to specific systems. Three of these types are shown in the photograph of Figure 1.

The Amplitron is a crossed-field device and consequently

TABLE I

SPACE AMPLITRON CHARACTERISTICS

	QKS997A	QKS1051	QKS1119	QKS1200
Anode Voltage V	1800-2000	1800	2450	1500
Anode Current mA	25	22.2	50	14
Power Output W	20	22	70	10
Frequency Mc	2200-2300	2295	2295	1700
Plate Efficiency	55%	55%	60%	55%
Heater Power (Run) W	0-4	0-4	0-3	0-4
Heater Voltage Preheat V	6.3	6.3	6.3	6.3
Drive Power mW	500	450	1760	100
Cooling	Conduction	Conduction	Conduction	Conduction
Weight	24 oz.	24 oz.	32-43 oz.	24 oz.
Size	2¾ dia. x	2¾ dia. x	2¾ dia. x	2¾ dia. x
(less connectors)	2¾ long	2¾ long	3 long	2¾ long

requires a dc magnetic field perpendicular to the basic flow of electrons from cathode to anode. In the tubes pictured the magnetic field is generated by two cylindrical magnets of Alnico VIII material. The tube anode together with the magnets are mounted inside of a steel can which provides the return path for the magnetic circuit, the thermal path from the rf structure of the anode to the cold plate on which the tube mounts, and mechanical support for the entire tube. This shell is 2¾ inches in diameter and either 3.4 inches long on the 70-watt version, or 2¾ inches long on the lower power types. The 20-watt tubes weigh only 24 ounces.

Because of the magnetic shell, the tubes are practically immune to changes in performance due to the presence of nearby magnetic materials. The stray field from the Amplitron is less than 200 gamma (10^{-5} gauss) at a distance of 3 feet from the tube.

Figure 2 shows the basic anode assembly of the QKS997A together with the cathode, a ceramic mounting washer and one of the pole piece assemblies necessary to complete the vacuum envelope.

One rather unique feature of the Amplitron which makes

Figure 1 — Three Raytheon CW Amplitrons developed for communications. Shown (left to right) are the QKS997A, QKS1051, and the QKS1119.

it attractive for many telemetry applications is the absence of attenuation in the rf structure. With no voltage applied, the tube behaves as a bandpass filter with an electrical length of only a few half-wavelengths. Its insertion loss in either direction is of the order of 0.5 to 1.0 db (Figure 3). Most of the common failure modes, especially of low power tubes, leave this property intact, and effective redundancy can be obtained by placing two identical tubes in cascade and switching voltages to the one selected for operation at a particular time (Figure 4).

The feed-through feature also permits multi-level operation at high efficiency. In the simplest arrangement, the driver is allowed to feed through a single Amplitron stage providing two output levels differing by about 20 db.

The absence of attenuation in the Amplitron makes it often desirable to include circulators in the system design to provide non-reciprocal attenuation. In general, the driver for the Amplitron must be protected by a circulator or isolator since reflections from the Amplitron load pass through the tube unattended (and unamplified). With a 20-db gain in the Amplitron, the load would have to be kept below 1.1/1 VSWR to prevent the driver from seeing a short circuit or worse. In addition, the Amplitron itself generates reverse directed power about 20 db below the output signal, and a circulator will prevent this from affecting the driver performance.

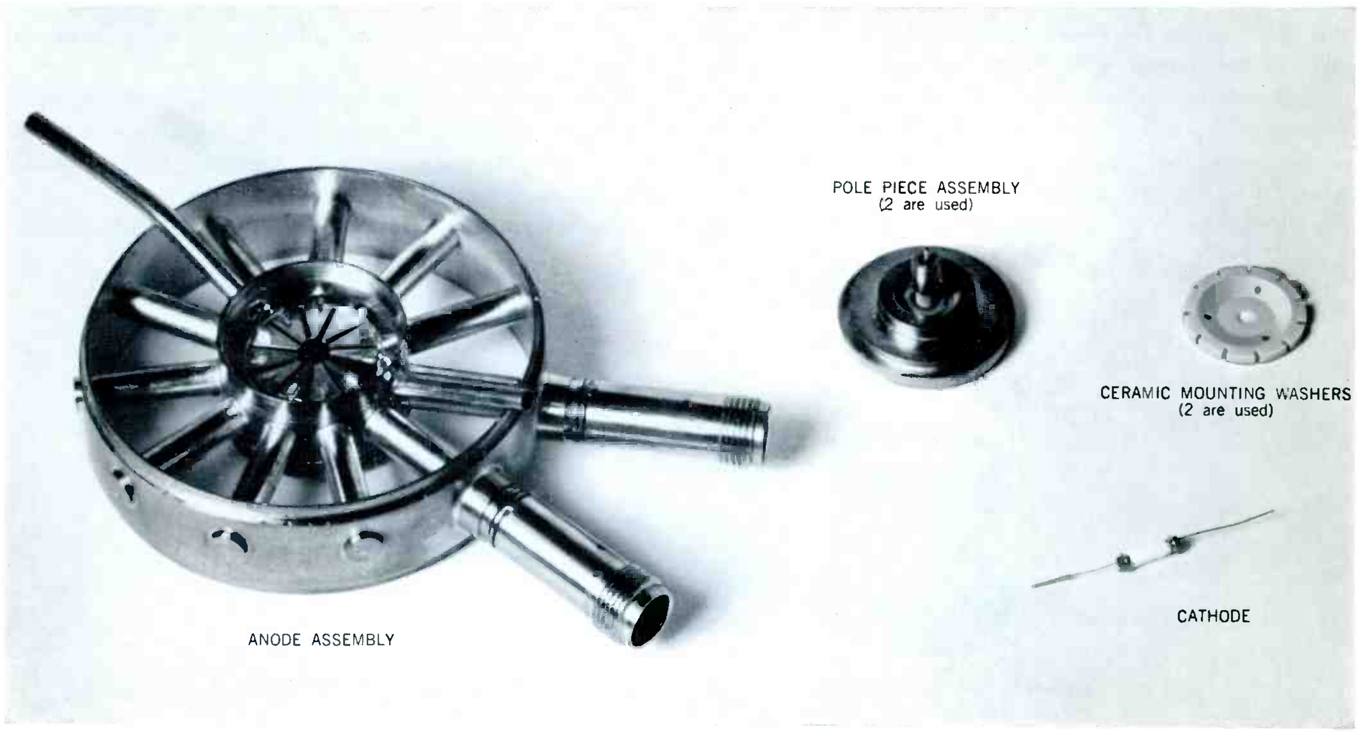
The Amplitron is a crossed-field continuous-cathode backward wave amplifier. In the QKS997, which has been developed specifically for spaceborne telemetry, an eleven-vane rf structure is employed to obtain electronic interaction with the $n = 4$ space charge mode.

The rf structure, shown in Figure 5, consists of a pair of straps forming a two-wire transmission line. This line is loaded by 11 vanes connected to alternate sides of this line. The vanes are primarily capacitive and they are shunted by coaxial cavities which are inductive (less than quarter-wavelength) at the operating frequency. Connections are made to either end of the two-wire line through coaxial line terminating in TNC female connectors. Dimensions of the coaxial lines are selected to provide appropriate impedance transformation between the anode structure and standard 50 Ω coaxial cable.

At the operating frequency, the phase shift along the two-wire line is approximately 3 half-wavelengths. The rf field distribution inside the anode hole is then 8 half-wavelengths — 11 180° phase reversals introduced by the alternate connection of the vanes minus 3 x 180° = 540° phase delay on the straps.

Electronic interaction with the wave traveling on the anode circuit can then be obtained with a space charge

Figure 2 — Parts of Basic Anode Assembly, CW Amplitron.



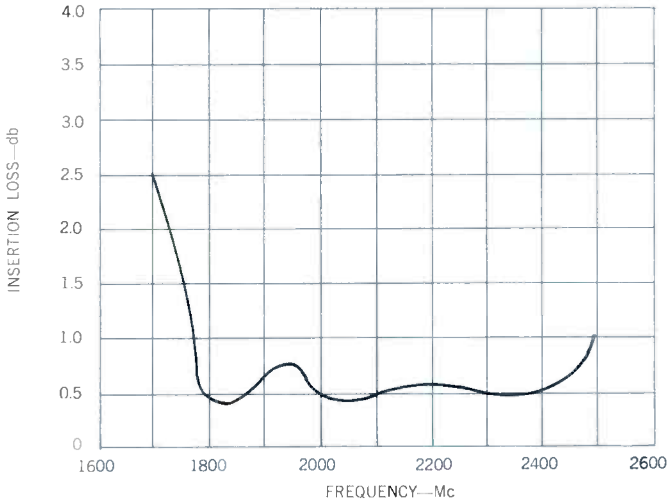


Figure 3 — QKS997A-101 Insertion loss through CW Amplitron.

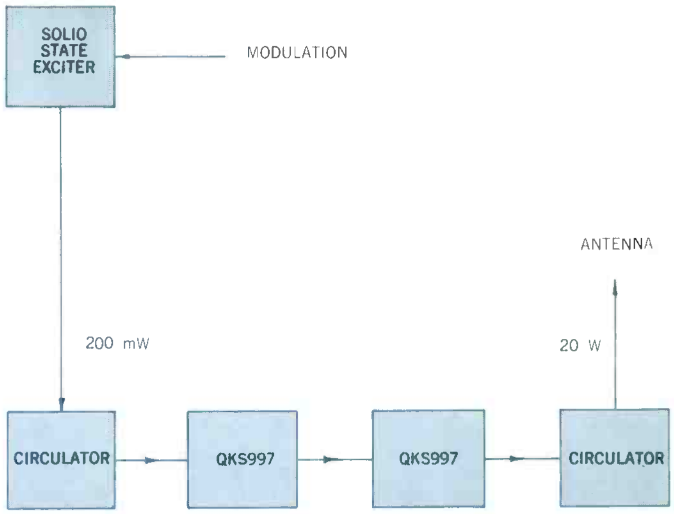


Figure 4 — Block Diagram, 20-watt Amplitron Telemetry System with redundant power stages.

distribution with four strokes, similar in many respects to the space-charge distribution in an oscillating 8-vaned magnetron. The operating parameters — magnetic field, anode voltage, efficiency — are calculated on the same basis as that of the magnetron.

In the case of the QKS997, the calculated $V_o = 192$ volts and $B_o = 487$ gauss at 2300 Mc. The selected operating point is $V = 1800$ volts with a magnetic field of 2200 gauss — $B/B_o = 4.5$. For this value of B/B_o, the theoretical efficiency is 87%. Efficiencies in excess of 60% are measured under these conditions.

The voltage-current characteristic of a CW Amplitron appears as shown in Figure 6. With rf drive present, a sharp "gauss line" or operating line appears near the voltage for optimum interaction at the frequency of the drive signal. This line is an impedance of only a few hundred ohms, compared to 500 to 100 kilohms for the static impedance of the tube. The maximum current that may be drawn on this line is a function of drive power. A plot of power output at the maximum current as a function of drive power is shown in Figure 7.

Also plotted in Figure 7 is a mathematical expression for gain in the Amplitron device derived by W. C. Brown and based on a rigid spoke theory of interaction. The power output plotted is the maximum that can be obtained by adjusting the power supply for maximum anode current at the drive level specified. The normal operating current is chosen at least 20% below this maximum level.

With the current held constant at a value less than the maximum value, varying the drive signal power has little effect on the power output. Any additional drive power above the minimum required passes through the tube and adds to the output without amplification.

With no drive power applied, the Amplitron will draw reduced current and produce a noisy output signal several megacycles wide centered at a frequency which is proportional to the applied voltage.

With drive applied, the anode voltage of the Amplitron must be held within narrow limits if amplification is to be obtained. This is generally accomplished with a power sup-

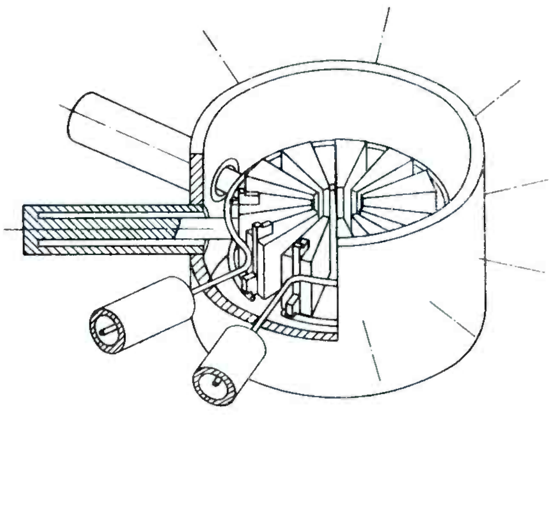


Figure 5 — Pictorial representation of the eleven-vaned rf circuit of QKS997A.

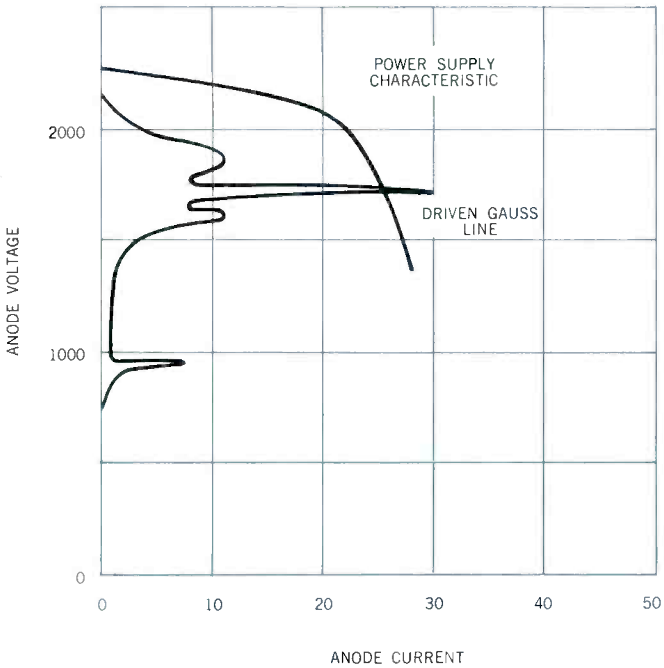


Figure 6 — QKS997A Voltage-Current Characteristics.

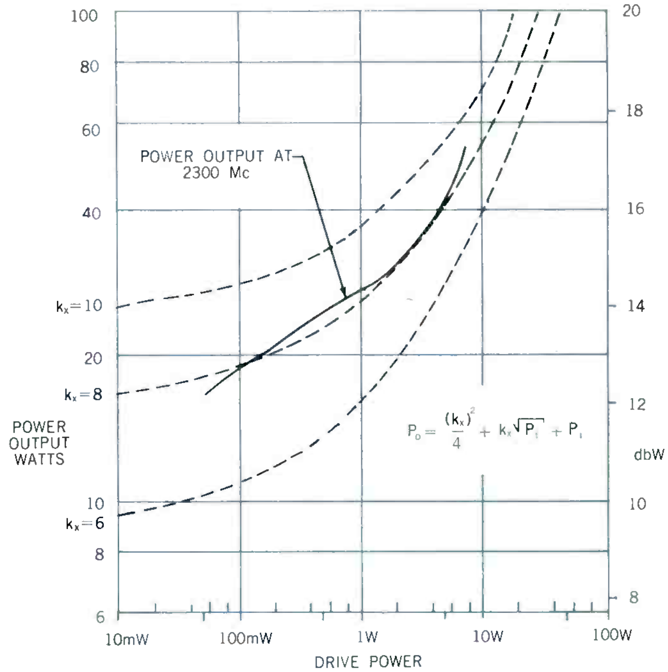


Figure 7 — Power output as a function of power input for the QKS997A with anode current adjusted for maximum at each drive power level.

ply which includes current regulation, as current is a sensitive measure of proper operating voltage. The simplest form of regulator is series resistance, but this is usually rejected for all except laboratory systems because of the power lost in the dropping resistor and the relatively poor regulation provided.

The series resistor may be replaced by a vacuum tube or transistor with appreciable gain in the feedback circuit. In this case, much improved regulation is obtained with less power loss but with added complexity.

The circuit of Figure 8 has been suggested by engineers of Raytheon's Magnetics Operation and Space Information Systems Division as a means of providing low frequency regulation at high efficiency and with minimal complexity. The regulation in this case is in the primary circuit of the high voltage transformer sensing current in the secondary. It provides stabilization against input line variations as well as any changes in tube voltage arising from changes in frequency, temperature, magnetic field or the effects of life.

In the circuit shown, a similar feedback scheme is used in the heater circuit which although not imperative appears desirable from several aspects. It assures good control of the heater power by sensing the heater current. It effectively limits the surge current when power is applied to the cold heater. It provides a convenient means to introduce the reduction of heater power desired as the plate power is applied to compensate for the back bombardment heating of the cathode.

As in the magnetron, some of the electrons emitted from the cathode of the Amplitron find themselves in the wrong rf phase. These accept a small amount of energy from the rf field and are driven back to the cathode. The excess energy which they have accepted from the rf field is converted to heat at the surface of the cathode. It is customary to reduce the heater power upon application of plate power to compensate for this heating effect.

These electrons striking the cathode surface also give rise to rather large amounts of secondary emission. In fact, some tubes, especially at higher powers, are operated with cathodes supplying only secondary emission. Several types of cathode operating near room temperature have been found satisfactory.

In the case of the QKS997, a conventional oxide-coated cathode with a nickel matrix developed at The Machlett Laboratories, Inc.,* has been selected. A cathode emitting area of nearly 0.4 sq. cm is provided so that primary emission densities at the 20-watt level are less than 60 mA/cm^2, a figure which in traveling-wave tubes is used to predict an operating life in excess of 40,000 hours. Because of the presence of back bombardment in the Amplitron emission lifetimes are expected to be somewhat less than those predicted at comparable temperatures without back bombardment.

*P. F. Varadi and K. Ettre, "Simultaneous Cataphoretic and Electrolytic Depositing Nickel for Plated Cathode of Reliable Electron Tubes," JAP.

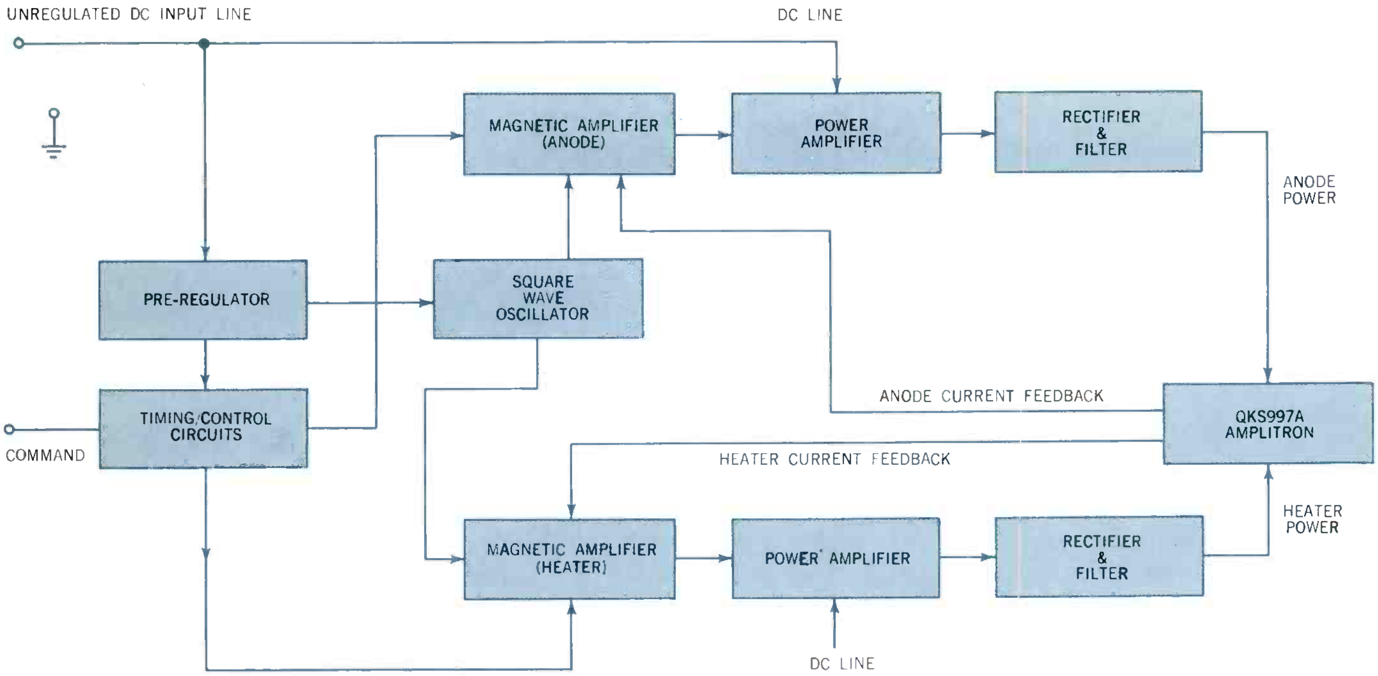


Figure 8 — Block Diagram, Amplitron Power Supply.

The space Amplitrons now being built at Spencer Laboratory are the first in which operating lifetimes greater than 10,000 hours have been the objectives of the development program. Much of the technology that has been generated by other devices has been incorporated into the Amplitron design. The validity of the translation of this technology can only be proved by extensive life tests which are currently planned.

The most critical question is, of course, the wear-out phenomenon of the cathode — to what extent can the secondary emission which is generated be used to reduce the demands for primary emission and consequently high temperatures and evaporation rates.

The ability of a cathode to supply adequate emission at low temperatures and for a long period of time is dependent on its operation in a vacuum envelope free from foreign vapors. Careful selection of materials for the vacuum envelope and advanced processing techniques including double vacuum bakeout at high temperature are employed to assure long life in the Amplitron.

The thermal design of the QKS997 is one factor which tends to reduce the possibility of gas evolution in the tube. The rf structure is designed to collect the entire electron current in normal operation. It is made up of copper parts at ground potential which provide an excellent heat path to the mounting plate. With 20 watts of dissipation, the temperature drop from the tips of the vane where electrons are collected to mounting plate is calculated to be less than 40°C.

The mechanical design of the tube is also such as to provide high resistance to damage from severe mechanical environments. Several tubes have been tested with 200g shocks in three mutually perpendicular planes without change in characteristics. Vibration tests with sinusoidal vibration at the 15g level in any of the three planes shows less than 1° rms phase modulation induced by the vibration. Data from one QKS997A is shown in Figure 9.

One of the more important characteristics with respect to frequency or phase modulated systems is the phase modulation due to power supply ripple or other sources. The relatively short electrical length of the Amplitron also contributes to a low pushing factor. The phase shift is less than 2° for a 1% change in anode current around the 20-watt operating point. Thus, a power supply with 1 volt of ripple and an internal impedance of 5000 ohms would introduce about 2° of phase shift. The phase modulation by noise is also low, less than 0.5° rms in a 500 Kc band pass. No measurable increase was found in the background of 1 to 2° in two separate systems in which a tube has been checked. An experimental tube has also been tested and found stable in a phase locked loop with a bandwidth of 20 cps.

The most serious limitation of the Amplitron for telemetry applications has been its relatively low expected gain. Most pulsed Amplitrons have been built for extremely high power operating point chosen to provide only 10 to 13 db of gain. As has been shown in the QKS997A development, however, proper selection of the operating point and good rf circuit design can yield Amplitrons which can be operated with nearly 20 db gain. At S-band, this gain is sufficient to bring the output of a solid state exciter to the 20 to 100-watt level in a single stage.

When higher gains are required, additional Amplitron stages are practical, especially where efficient operation at several power output levels is desired. Figure 10 is a block diagram for a system in which three levels would be available — the 200-mW level of the solid state driver, the 20-watt level of the driver-Amplitron, and the 500-watt level of the final Amplitron. (The QKS1115 is currently under development.) Both of the Amplitron stages could be 60% efficient in S-band. Ferrite isolators would be included to provide non-reciprocal attenuation at least equal to the power gain. The diagram also shows two tubes for each stage to provide redundancy as has been discussed earlier.

Amplitrons are not restricted to telemetry in S-band but can be effectively scaled for operation throughout the microwave spectrum. The magnetic field required for efficient operation increases directly with frequency, and permanent magnet and pole piece materials place a practical upper limit on frequency around 100 Gc. At L-band and lower frequencies, the competition with solid-state devices will limit the applications except for fairly high powers. Units in the 100 watt to a few kilowatt range appear quite attractive at S, C and X-band and from a few watts to a few hundred watts in the higher bands. Lower power units appear to be probable at the higher frequencies to match the output power available from solid state drivers. The upper limit on power output is a function more of spacecraft available power and of adequate cooling techniques as the basic interaction process has been shown to be capable of super-power generation.

Figure 10 — Block Diagram, 500 Watt Telemetry System with two stages at amplitron amplification and redundant tubes in each stage.

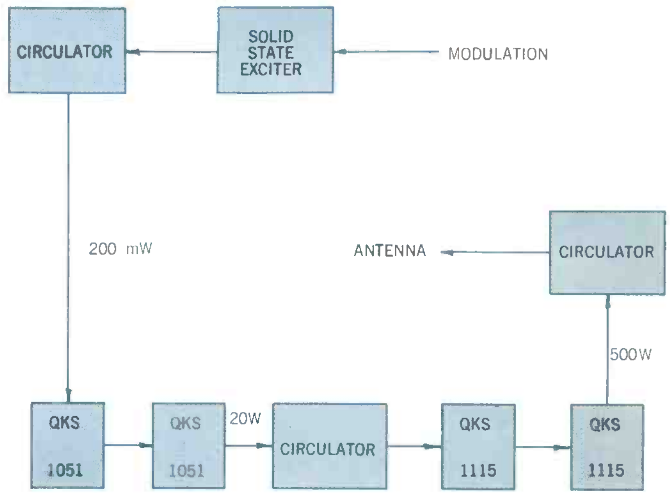
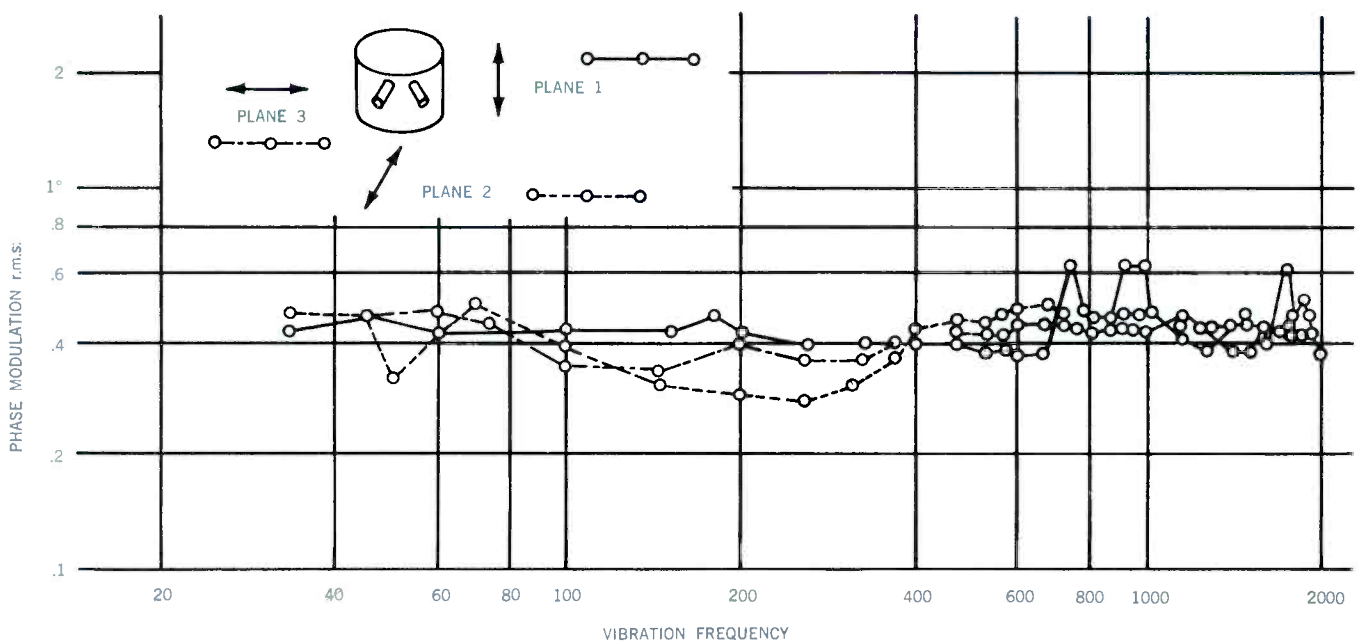
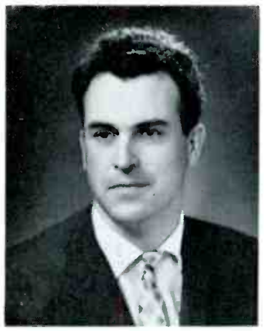


Figure 9 — Phase modulation during sinusoidal vibration, QKS997A-102 CW Amplitron, driven at 2300 Mc. Vibration level 15G at frequencies shown.





WERNER BRUNHART

Werner Brunhart joined Machlett in 1954 as a design engineer in the development of hydrogen thyratrons, pulse modulators and UHF triodes. He has been Chief Engineer, Small Power Tube Products, since 1962. Mr. Brunhart was graduated with an M.A. in Electronics from the Swiss Federal Institute of Technology in Zurich. He became an instructor there in 1951, serving the school's Advanced Electrical Engineering Department.

Negative Grid Tubes for Space Applications

By WERNER BRUNHART, Chief Engineer, Small Power Tubes; The Machlett Laboratories, Inc.

Introduction

The main requirements for any electron device in outer space applications is good overall efficiency, long reliable operation, a package as small and light as possible, and capability of withstanding severe environmental conditions. These requirements are not usually compatible with each other. With respect to power output and plate efficiency, the negative grid tube is only surpassed by other devices operating at higher frequencies. With respect to power gain per stage, other tubes, such as TWT's, etc., are superior to the negative grid tube. Despite this, the negative grid tube has not only been selected for space applications in the past, but also for future applications. Following are some of the advantages of the negative grid tube. No magnetic field is required which could disturb other functions in a spacecraft. Circuits employing this tube are simple and can withstand very stringent environmental requirements of up to 100 G's shock, and vibration over a wide range of frequencies up to 20 G's and more. The power supply required in conjunction with the tube does not require extensive regulation. In some cases the regulation can be omitted altogether without adversely affecting operational stability, especially with respect to frequency. The effect of nuclear radiation on tube operation is negligible.

Following are procedures which are used in the fabrication and testing of negative grid tubes which are specifically designated for space applications.

Fabrication of the Tubes

Even though tube fabrication normally requires clean and careful assembly techniques to assure a good product, it is necessary to improve these techniques still further. All ceramic parts (only metal-ceramic envelopes are used) used for these special tubes are individually inspected for cracks and chips using a microscope with a 10X magnification. In standard tube production, parts sampling is considered adequate. With special tubes, each ceramic part is again checked after metalizing for defects by backlighting. Every tenth piece is used to monitor (see Figure 1) the thickness of the metalizing (the method used is destructive). The above inspection procedure is repeated after each operation.

The metal-ceramic sub-assemblies are all radiographed for possible solder voids, and are then leak tested. In normal production, each part is checked only for leaks. However, it is felt that parts with solder voids, which are not detectable in standard tube procedures might eventually develop small leaks and require the discarding of the whole assembly.

All other tube parts receive a 100 per cent inspection, usually by engineering personnel. For instance, each grid is carefully checked for uniformity with regard to wire spacing and tension. Furthermore, each weld on the various sub-assemblies is inspected by means of a microscope. And last, but not least, the cathode assembly receives special attention to assure a clean and passive cathode emitter with uniform emitter coating.

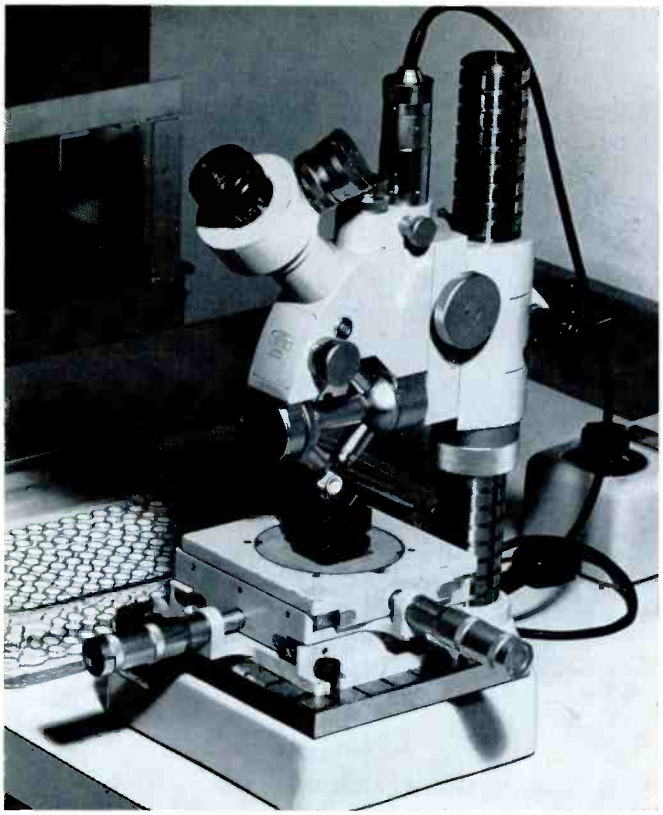
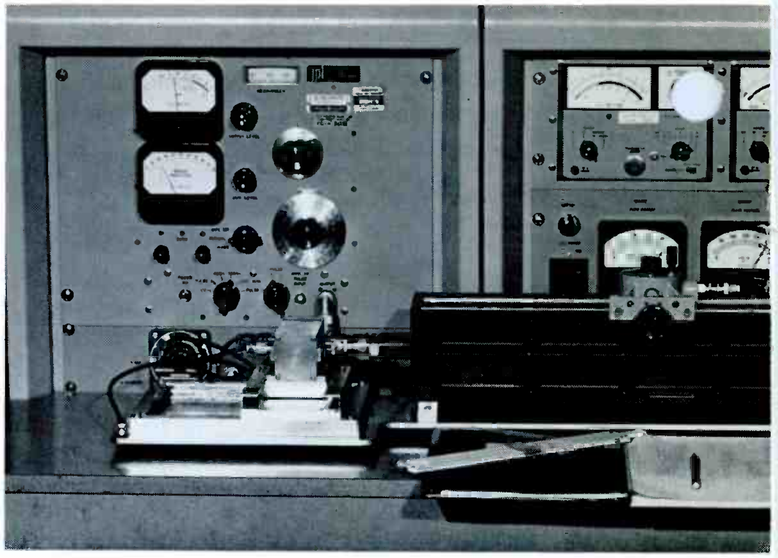


Figure 1 — Thickness of metalizing on ceramic parts are checked with specially adapted microscope.



Figures 2 and 2A — Final testing of ML-6771 planar triodes for space application takes place in this power gain test set, which employs a microwave amplifier, slotted line and pre-tuned cavity. Even though this extremely precise test unit is highly stable, it is recalibrated prior to each test. At a test frequency of 960 mc, ¼ watt input, the typical output power range is 3.1 to 3.4 watts. Average VSWR readings are 1.4 to 1.45 — well below the "not-to-exceed" 1.85; readings as low as 1.1 have been made. Figure 2A shows a closer view of the Resdel amplifier cavity, preset to accept only those tubes within a narrow tuning range.

Immediately after final assembly, all special tubes are radiographed and examined for proper location of the various elements. A leak check is performed just prior to the exhaust cycle of the multiple exhaust station to assure that no contamination takes place during this test operation.

Testing of the Tubes

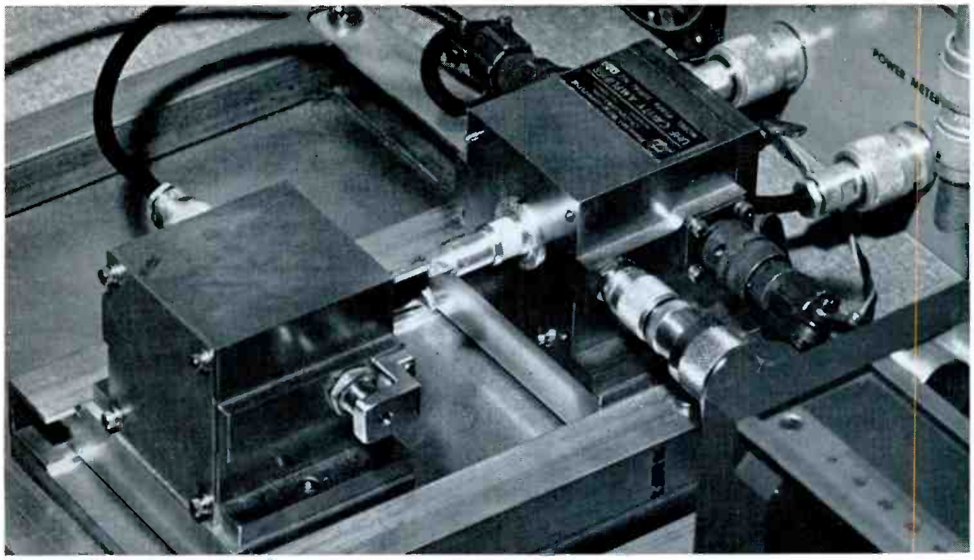
After aging, the tubes are subjected to the normal static tests in order to verify that their characteristics are acceptable. Over and above these standard tests, it is mandatory that each tube be tested in the final equipment circuit under actual flight conditions (see Figures 2 and 2A). Only this test really proves if the tubes are acceptable. The test in the final equipment is repeated a second time. The first test is done only after the tubes have been shelf-aged for several days. Only tubes which repeat original test data within the accuracy of the instruments are accepted. After this the tubes receive an ambient temperature cycle of about — 62°C to + 150°C. Then, the final test is again performed in the flight test circuit.

At this point the tubes are shipped to the user, who then conducts his own series of tests. The tubes are tested in the final circuit for at least 100 hours, during which time they are subject to shock, vibration, ambient temperature changes, etc. Only tubes which perform well and show no performance changes up to this point are accepted for flight equipment. In the flight equipment itself, all components undergo extensive testing which can last up to 1000 hours.

Actual Applications

To date the following tube types have been and are being used in space applications — the ML-471 (a special version of the 6442) in the Project Mercury S-Band beacon, the ML-6771 in the Project Mercury C-Band beacon, the ML-546 (a special version of the 6771) in Projects Mariner and Ranger transmitters, the ML-7855 in the TV transmitter for Project Ranger, and the ML-518 in the frequency multiplier and amplifier of Project Nimbus telemetering system. There are other applications of these tubes in various other military missiles.

Above is mentioned the importance of testing the tube in final flight circuits and conditions. This includes, of course, the filament voltage. The selection of the proper optimized filament voltage is very important. The tube life can be drastically shortened if the filament voltage is set wrong. Life tests of tubes used in Projects Mariner and Ranger indicate that the same power output can be obtained with a filament voltage of 5.2 or 5.75 volts. However the drop in power output is about 1.5 db for an amplifier chain of two tubes over a period of 15,000 hours in the first case,



and about 9.7 db in the second case; see Figures 3 and 4. This example points out the importance of the filament voltage. It also indicates that the plate power supply can be of a rather simple design and the operating conditions, (i.e., plate current and plate dissipation) have only a minor influence on the life of the tube once conditions have been optimized. At least the final amplifier tube used here is operated close to maximum ratings with respect to plate voltage and current, maximum plate power input is rated at 6.25 watts. In this application, the tube is operated at about 5.25 watts, with a minimum power output of 3.1 watts. The current loading of the cathode in this case is approximately 150 ma/cm^2. It should be emphasized that no self compensating circuit was employed to automatically adjust the current for changes in the tube characteristics.

Acknowledgment

The author acknowledges with pleasure the contributions made by R. F. Spurck toward the establishment of the manufacturing and processing procedures.

Figure 3 — Power Output versus Time for ML-546 of the Preamplifier used in Mariner and Ranger Transmitters.

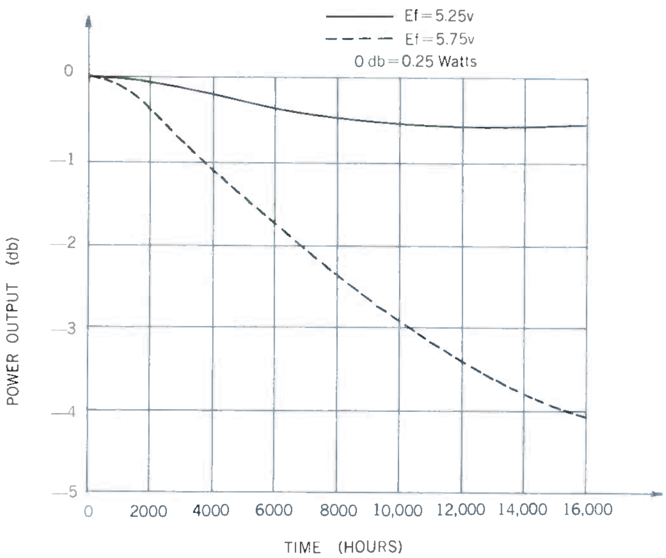
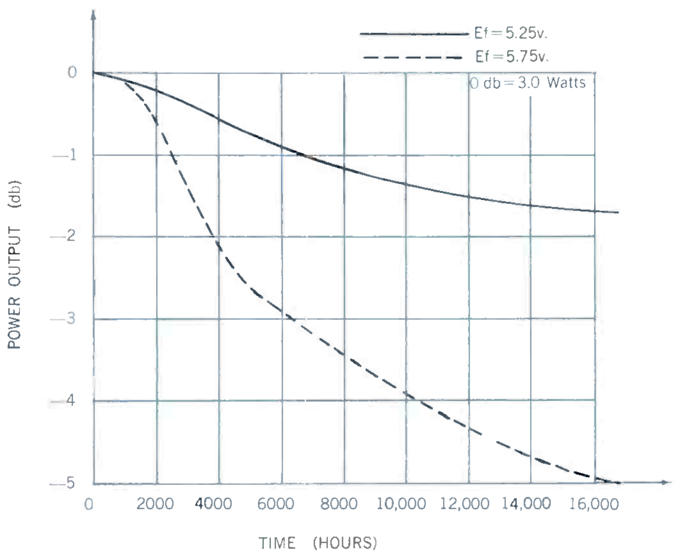
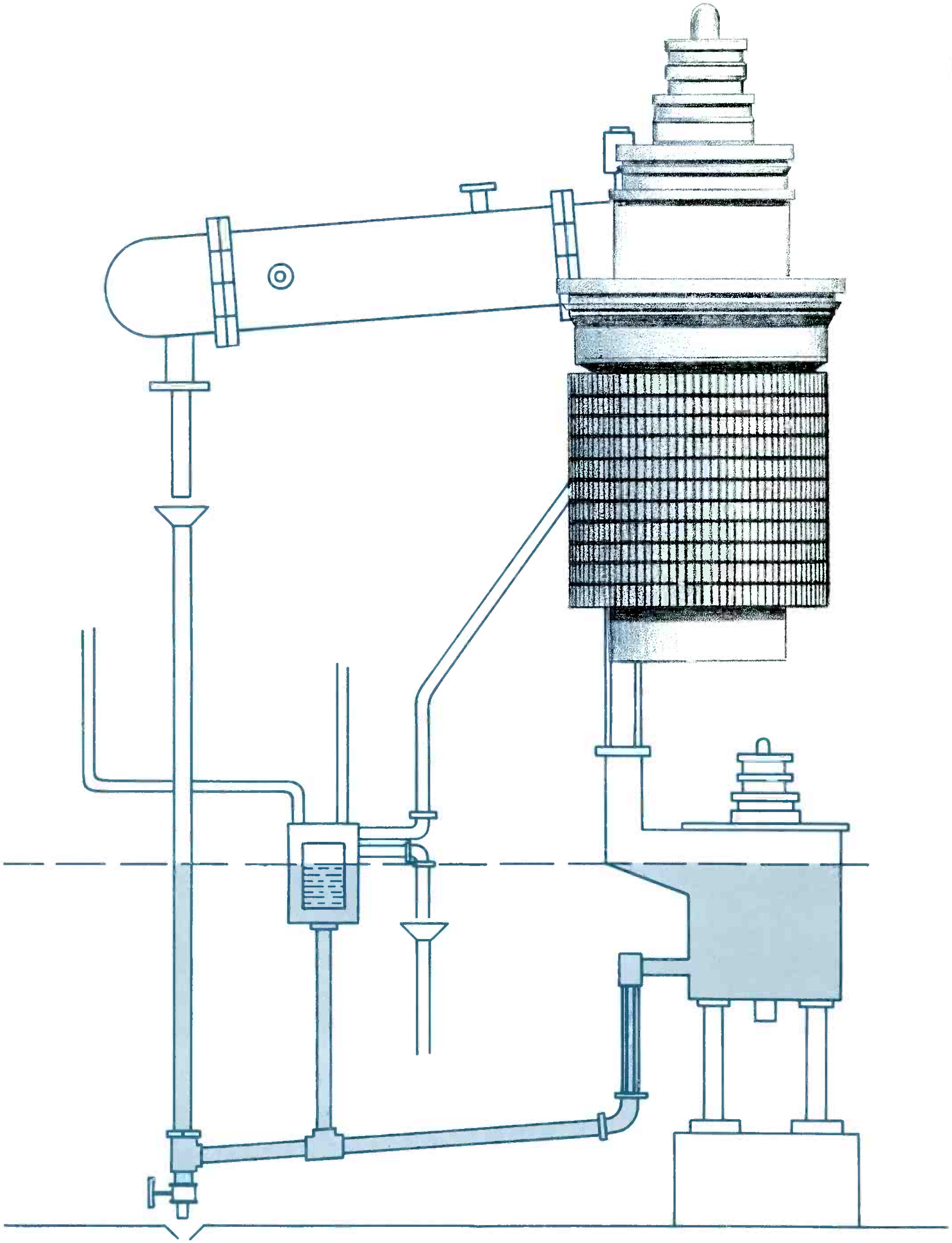


Figure 4 — Power Output versus Time for ML-546 of the Final Amplifier used in Mariner and Ranger Transmitters.





Notes on Vapor Cooling of High Power Electron Tubes

By HELMUT LANGER, Senior Development Engineer

and

JOSEPH FEDORCHUCK, Development Engineer

Since vapor cooling of high power electron tubes was introduced some 12 years ago, it has become a subject of increasing interest among equipment designers. Because of its inherent advantages as well as its supplementary advantages, vapor cooling has become a process proven to have superior cooling capabilities for many applications, especially those involving high power tubes. From the economic standpoint, vapor cooling is not only proving advantageous in new equipment, but it has demonstrated its value in recent conversion applications which previously employed air-cooled power tubes.

Vapor-cooling systems involve several design considerations which are not normally associated with radiation, forced-air, or forced-liquid cooling. It is the purpose of this article to outline some of these design considerations, as well as to introduce some entirely new aspects of this subject.

Heat Transfer to Boiling Liquids

Experiments on heat transfer to boiling liquids have shown that vaporization and creation of vapor bubbles often start at microscopic cavities. At a point on the anode where a vapor bubble is formed, the coefficient of heat transfer is greatly reduced until the bubble is set free. For the most part heat transfer occurs mostly at points on the anode where momentarily no vapor bubble is present. Removal of the vapor bubble is accomplished by the convection current of the liquid, i.e., thermosyphon effect. As long as the temperature difference Δt of the anode and the liquid is relatively small, flow of the liquid and enclosed vapor bubbles stays laminar. With increasing temperature of the anode, the vapor bubbles become larger. As more bubbles are formed and are crowded in the same unit area, the vapor-liquid emulsion becomes turbulent. Figures 1, 2 and 3 are photographs illustrating bubble formation on a Machlett ML-7482 super-power triode tube at different plate dissipation levels. Maximum heat transfer in water is accomplished at Δt of approximately 25°C (see Figure 4). With increased Δt, the heat transfer rate is decreased by formation of a vapor film on the anode surface which acts as an insulator by greatly reducing the heat-transfer rate. Also, this vapor film could cause overheating and possible burn out (calefaction) between M and L (Figure 4), resulting in an overheated anode with subsequent gassing and possible tube destruction. Therefore, a change from the nucleate boiling ($\Delta t < 25°C$) to film boiling ($\Delta t > 25°C$) results in irreversible overheating. The maximum heat flux

$\frac{Q}{A}$ would be limited to 135W/cm^2.

Heat Transfer in Vapor-Cooled Structures

Danger of overheating in the transition zone (M-L) (Figure 4) can be avoided when the surface of the anode

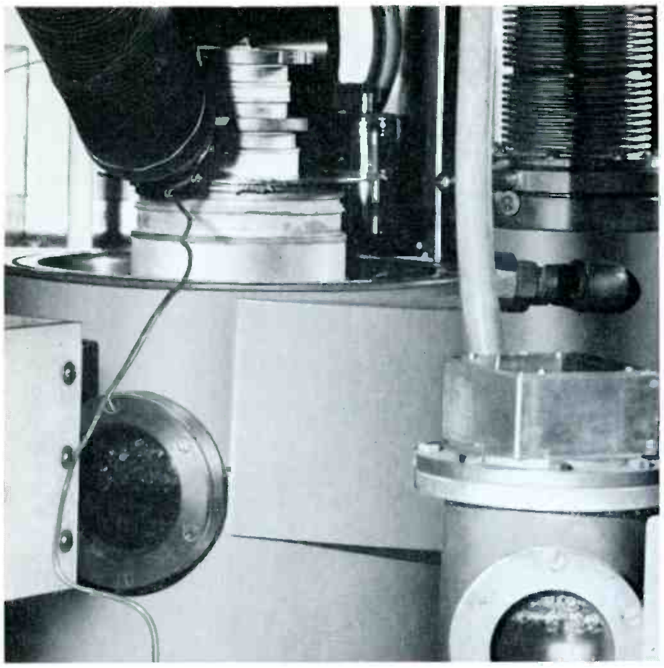


Figure 1 — ML-7482 Super Powered Triode under test in "classical" system boiler at 100 Kw plate dissipation. Note boiling action about anode visible through porthole at left.

Figure 2 — Closeup of porthole shown in Figure 1 with tube operating at 150 Kw plate dissipation.

is provided with heavy protrusions, as has been developed by CFTH (France) in their early pineapple design[1]. This design was later modified to a straight gear type anode design as is shown in Figure 5, probably for economic reasons. Another design which is used by Telefunken, Germany and others, utilizes a very heavy wall anode with many large holes drilled axially through the anode wall near the outer edge[2&3]. The aforementioned anode fin tube design allows heat removal of about 200W/cm^2, in terms of the inner (vacuum-side) bombarded anode surface. The heat removal rate in terms of the outer corrugated surface is in the range of 35W/cm^2. A still later improvement developed by CFTH uses a large number of rather small, but deep radial slots. The first test results by CFTH and by Machlett indicate heat transfer capabilities of this tube in the order of >500W/cm^2. Figure 6 shows a Machlett ML-7482 tube with a third generation fin design, which increases plate dissipation capabilities of the anode over previous generation tubes from 200 kW to 300 kW. Safety for short time overloads is maintained.

It should be noted that radial extension within proper design configurations increases the heat dissipation of the outer anode surface by a factor of 5 to 10. This radial extension also permits the operation of the anode in the critical transition zone without danger of burn-out. If a vapor film adheres to one local section of the fin, then heat transfer is accomplished at another section. As power dissipation is increased, more vapor bubbles are formed and more turbulence of the water-vapor emulsion is accom-

Figure 5 — ML-7482 (second generation anode fin design). P_A = 200 Kw.

[1]C. Beutheret, "The Vapotron Technique," *Review Technique*, C. F. T. H. No. 24, Paris, December 1956.

[2]C. Protze, "KanalKuehlung, eine Siedekuehlung von Hochleistungs HF-Generator und Senderoehren," *Telefunken Zeitung*, Vol. 29, No. 112, June 1956.

[3]J. Houdyshel, "Vapor Phase Cooling of High Power Equipments," *Electro Technologie*, March 1963.

Figure 3 — Closeup of porthole shown in Figure 1 with tube operating at 200 Kw plate dissipation.

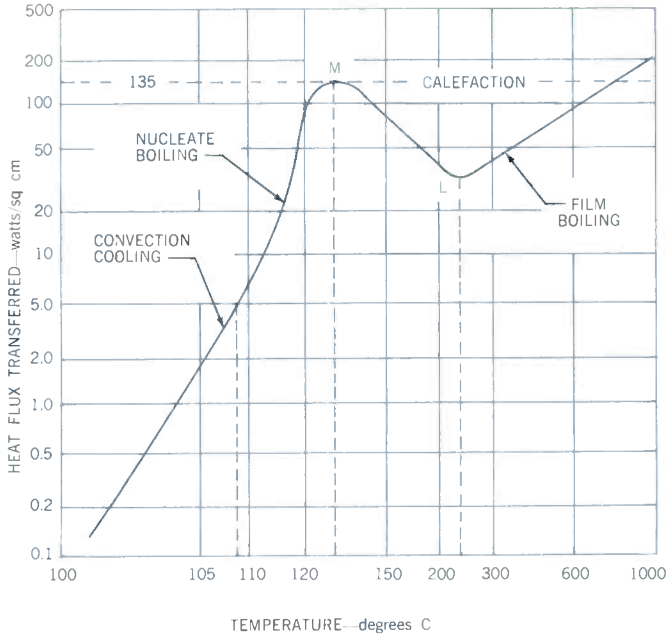
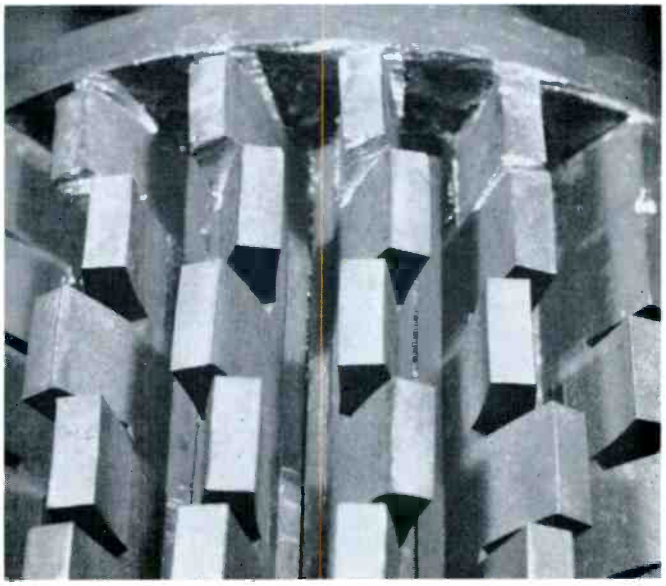


Figure 4 — Nukiyama Heat Transfer Curve For Boiling Water.

plished, and thus better contact of the liquid to the anode fins takes place. Experiments have shown that so-called "twisting" of the fins (see Figure 7) on a gear type anode increases the heat transfer rate of the anode by more than 30%. At the same time, the twisted fins provide a more quiet operation from the standpoint of mechanical vibration of the tube-boiler assembly. In the earlier anode-fin designs — pineapple gear type, or channel cooling type — the vapor-water emulsion was ejected at the upper opening between two fins, as directed by a rather closely surrounding jacket which creates a thermosyphon effect. In the newer fin designs with small, deep grooves (see Figure 6) vapor bubbles are free to move radially outward, forming a vapor cloud a safe distance (½" to 1") away from the outer

Figure 6 — ML-7482 (third generation anode fin design). $P_A \geq 300$ Kw.

Figure 7 — Closeup section of "twisted-fin" anode (experimental design).



external surface of the anode fin, and moving upwards towards the boiling liquid surface. One may observe this phenomena in Figure 2. Figure 8 is taken from C. A. Beutheret[4] and shows the curve of Figure 4 in terms of $K = \frac{Q}{A\ (\Delta t)}$ as total thermal conductance of vapor-cooled tubes with fin configurations as discussed above. Note that heat-transfer rates are increased from 150W/cm^2 in Curve 2 to as high as 600W/cm^2 in Curve 4. The transition zone C (see also Figure 4), is represented by a broken line. The efficiency curves drop rapidly when maximum thermal conductance is reached, and the structure would be subject to destruction if the power were not reduced in sufficient time. The curves in Figure 8 represent operation under steady state conditions in boiling water under atmospheric pressure.

Heat Transfer and Surface Conditions

Sufficient heat transfer under steady state conditions in vapor-cooled anode structures requires utmost care with respect to cleanliness of the boiling liquid, surface conditions of the anode structure and all system components. Generally, distilled water should be used in order to avoid sludge and scale formation on the anode surface, and to reduce the possibility of electrical breakdown in the insulated water intake due to high conductivity of the water[5]. However, clean tap-water can be used when certain precautions are taken. Clean copper in contact with the boiling liquid appears to give optimum heat transfer; slightly dirty copper can reduce heat transfer rates by 20% to 50%[6]. Oil or grease in the system will greatly reduce heat transfer and may produce carbonaceous scale deposits on the fin surface. Roughing of the anode-fin surface does not necessarily have positive effects on heat transfer. Proper acid cleaning and careful handling will, however, prevent contamination.

Aeration of the distilled water, as may be accomplished on the outlet of the heat exchanger (see Figure 10) may increase heat transfer[7]. Also, the addition of wetting agents to the distilled water may increase heat transfer by greatly reducing surface tension, thus permitting a freer escape of vapor bubbles. However, in using wetting agents, caution must be exercised to avoid scale formation.

Surface Scale Formation

The use of distilled water as the boiling liquid and the thorough rinsing of the anode fin surface by powerful turbulence greatly reduces scale formation. In a "clean" system, the anode-fin surface, after several thousand hours of operation, should still only exhibit a typical brownish copper oxide appearance. This condition is established after several hours of operation under maximum power dissipation of the tube. In an initial installation frequent rinsing of the overall system, including the heat exchanger, is required to remove most of the contaminants. After a system is put into operation, it is good maintenance practice to periodically drain the system and clean the anode structure and system components. Such practice will pay dividends in reliable system performance and excellent tube life.

Application of Vapor Cooling at High Elevations

Under normal conditions, vapor-cooling of high power tubes can be used at high elevations (transmitter or radio equipments at mountain tops) without loss of efficiency in heat transfer. Figure 9 shows the decrease of heat of vaporization of water with respect to saturation temperature and elevation in feet. Heat of vaporization at 15,000 feet is decreased by 1.8%. For example, at this altitude, boiling water absorbs approximately 535 calories per gram of water vaporized as opposed to 545 calories absorbed at sea level.

Applications of vapor-cooled systems at high elevations have several distinct advantages over forced-air or forced-water cooled systems.

1. Eliminates requirement of large amounts of circulating water for forced-water systems, which is difficult to provide at high elevation transmitter locations.
2. Dissipates 200% to 300% more power than air-cooled systems.
3. Provides significant supplementary advantages: practical means of using dissipated heat for heating buildings; and, efficient means of extracting distilled water from system[8].

Vapor Cooling at Subzero Temperatures

Many present day electron tube cooling systems must operate in remote areas under subzero temperatures. Systems using water must therefore be protected against the possibility of freezing during shutdowns or power failures. In general, water-ethylene-glycol mixtures are most frequently used (50% water-50% ethylene-gylcol for approximately —40°C freezing point). For forced-water cooled and vapor-cooled systems, only purified glycol and water solutions without additives should be used[9], as additives usually reduce the heat transfer rate. If the heat densities are high enough, local scaling may result. Machlett tests

[4] C. Beutheret, "Evaporation Process and the Vapotron."

[5] "Note on the Vapotron," Publication by the Compagnie Française Thomson-Houston, France.

[6] W. McAdams, Chapter X, "Heat Transfer to Boiling Liquids," *Heat Transmission*, McGraw-Hill, New York.

[7] Ibid.

[8] H. Langer, "Supplementary Advantages of Vapor Cooling: Space Heating and Distilled Water Production," *Cathode Press*, Vol. 20, No. 1, 1963.

[9] A. Winslow, "Coolants for High Power Radio and Transmitting Tubes," *Electronic Packaging and Production*, February 1963.

indicate that 50/50 glycol-water solutions and distilled water exhibit comparable boiling characteristics and heat transfer values. However, until sufficient field life data have been accumulated, plate dissipation values should be limited to approximately 75% of the maximum tube ratings, and rather frequent maintenance checks should be made.

With systems using glycol-water mixtures, evaporation losses on the outlet of the heat exchanger will consist mainly of water. To replenish the loss, only water has to be added. However, vapor-cooling systems normally include automatic water level controls which replenish the system from a reservoir. In most cases, it will also be necessary to maintain a glycol-water mixture in the reservoir. After a period of time, systems which initially included a 50-50 mixture, will consist of more glycol than water. It will then be necessary to institute periodic specific density tests, and if necessary replace or modify the solution to maintain the proper solution. The specific density of a 50-50 solution is 1.072g/cm^3 at 60°F.

Vapor Cooling for High Frequency Applications

In conventional vapor cooling systems, the water-steam emulsion at the upper escape provides an excellent means of cooling the anode flange. This feature permits the use of a short connection between the metal tube flange and the ceramic or glass envelope. It also reduces high frequency losses, which ultimately decrease the tube power output at high frequencies. The escaped vapor can either be discharged through an upper steam-tube, as in the Classical System (Figure 10), or it can be discharged downwards as in the Vapor-Down System (Figure 11). The latter system is of interest when considering that in high frequency applications, grounded grid operation is widely used. Discharge of the vapor downward permits tube designs with very short distances between the anode and the grid. This minimizes inductance, and subsequently increases the resonance frequency of the grid-anode circuit. While the Classical System operates without "external" power, the Vapor-Down System requires a small circulating water pump to feed the condensate back into the boiler, which is pumped at a rate 3 to 5 times more than would normally be required to compensate for losses due to vaporization. For very high frequency applications > 100Mc the Integrated High Frequency System is recommended (Figure 12). In this system the boiler becomes a part of the tube. However, the boiler-tube assembly is installed in an inverted position. The system is then operated in the same manner as the classical vapor cooling system. Advantages of this system include the reduction in size of the anode-boiler, which results in lower tube circuit capacitances that are essential in VHF installations.

Figure 8 — Conductance of Vapor Cooled Tubes.

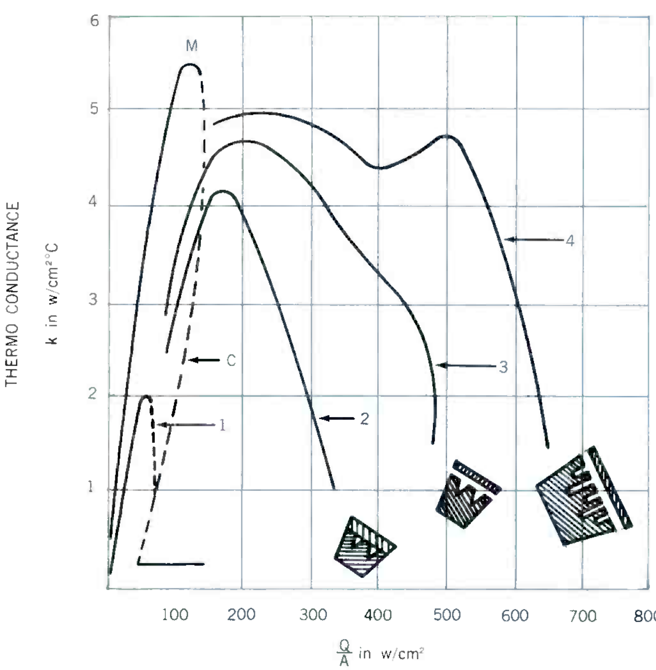
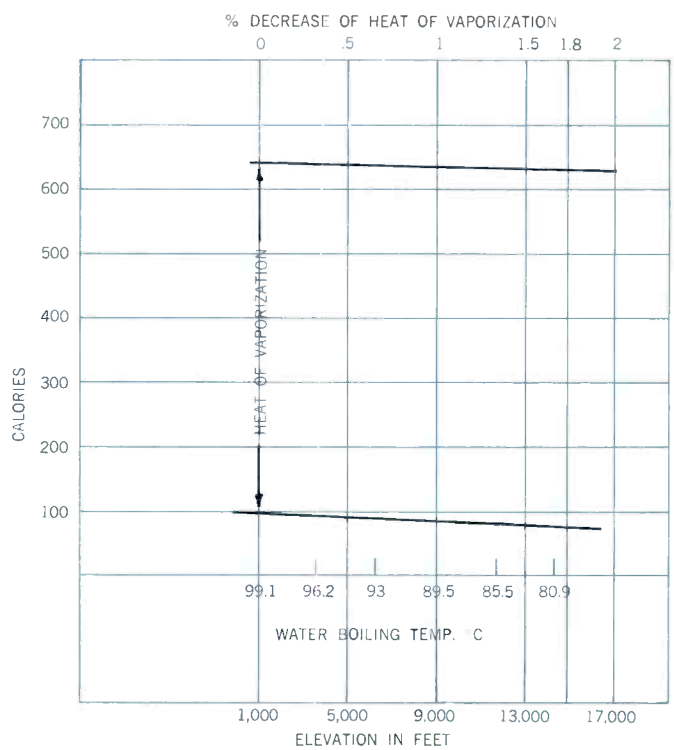


Figure 9 — Heat of Vaporization of Water versus Elevation in Feet.



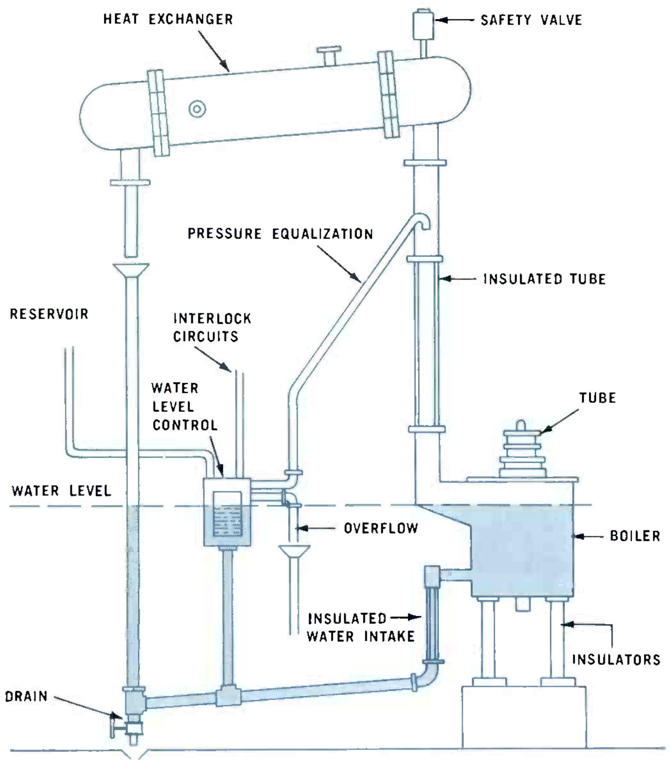


Figure 10 — Classical System. In this system the water-steam emulsion at the upper escape provides an excellent means of cooling the anode flange, permitting use of a short connection between the metal tube flange and envelope. This reduces high frequency losses which decrease the tube power output range at high frequencies.

Economic Considerations

In any discussion of the relative merits of cooling systems for electron tubes, installation and operation costs necessarily assume a major role. In many applications the selection of vapor cooling is easily justified on costs alone[10]. Generally speaking, installation costs for vapor cooling systems for high power tubes are somewhat higher than air-cooled systems; installation costs are comparable with forced-water systems. However, when total operational costs are considered, cost savings in favor of vapor cooling increase with dissipation levels. For example, operating costs for 5000 hours of operation at 50 KW dissipation are approximately $500.00 in favor of vapor cooling; and $1000 at the 100 KW level.

Another economic factor of vapor cooling can be translated in terms of tube life. There are some indications that vapor-cooled tubes, due to maintenance of constant anode temperature, now have greater tube life expectancy than comparable air-cooled tubes.

[10] M. Stangl, W. Allen, "Vapor Phase Cooling of High Power Electron Tubes," *Electrical Design News,* May 1962.

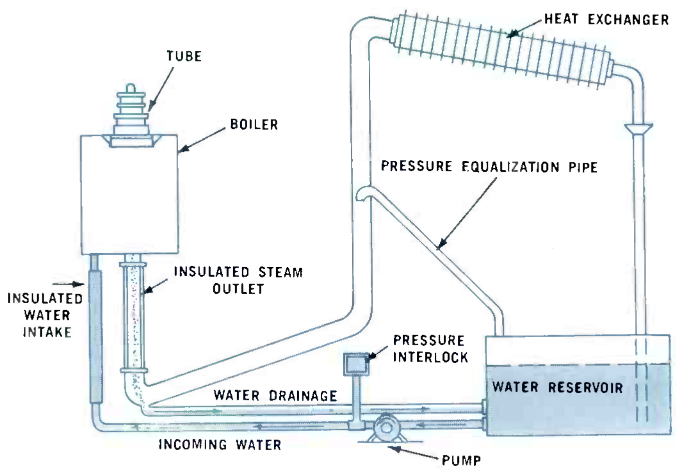


Figure 11 — Vapor-Down System. This system is to be considered for high frequency applications when grounded grid operation is used. The downward discharge of the vapor permits tube designs with very short distances between the anode and grid. This minimizes inductance, and subsequently increases the resonance frequency of the grid-anode circuit.

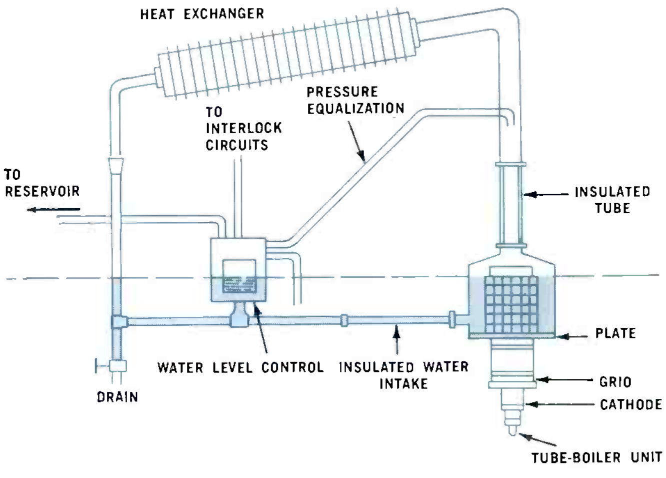


Figure 12 — Integrated High Frequency System. This system, in which the boiler is an integral part of the tube, is recommended for very high frequency applications greater than 100 Mc. Advantages of this method include the reduction in size of the anode-boiler, which results in lower tube circuit capacitances that are essential in VHF installations.

New Machlett Developments

ML-8495

High voltage triode for pulse modulator service to 3 Mw

Designed to operate primarily as a switch tube in pulse modulators and other high voltage switching applications. Employs sturdy thoriated tungsten filament and integrated forced-oil-cooled anode.

Maximum Ratings Pulse Modulator or Pulse Amplifier

Plate Voltage	160 kV
Pulse Cathode Current	22 amps
Plate Dissipation	2.5 kW

Typical Operation

DC Plate Voltage	150 kV
DC Grid Voltage	—1000 v
Pulse Positive Grid Voltage	1000 v
Pulse Plate Current	18 amps
Pulse Grid Current	3 amps
Pulse Driving Power	6 kW
Pulse Power Output	2.4 Mw
Pulse Output Voltage	135 kV

ML-7482

General purpose, vapor-cooled triode capable of 400 kW service at 30 Mc

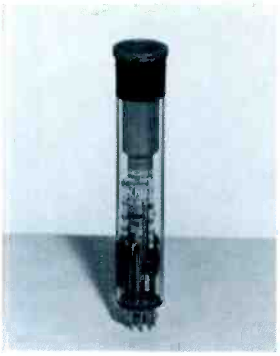
New ML-7482 general purpose triode is capable of more than 400 kW continuous output as Class C amplifier or oscillator at frequencies to 30 Mc. Improved anode design dissipates up to 300 kW during momentary overloads.

Maximum Ratings as RF Power Amplifier and Oscillator Class C Telegraphy

DC Plate Voltage	20 kV
DC Grid Voltage	—1500 v
DC Plate Current	30 amps
DC Grid Current	4 amps
Plate Input	600 kW
Plate Dissipation	200 kW

Typical Operation

DC Plate Voltage	20 kV
DC Grid Voltage	—1000 v
DC Plate Current	29 amps
Driving Power, Approx.	6 kW
Power Output, Approx.	440 kW



ML-589

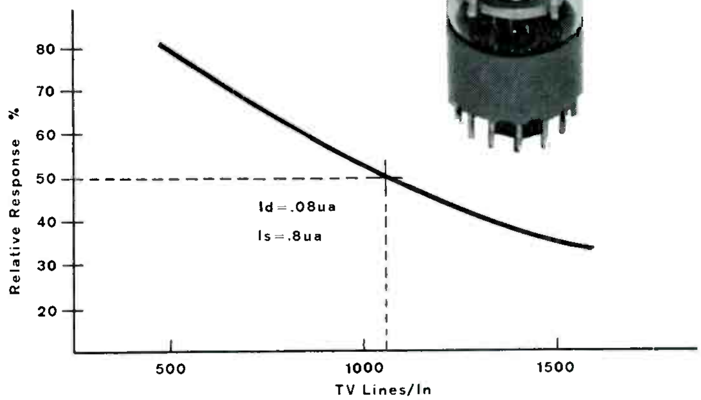
1″ X-ray sensitive vidicon for static and in-motion TV/x-ray systems

ML-589 "Dynamicon" provides high contrast images with detail resolution down to 0.0005″, and penetrameter sensitivities up to 2%, when used with an adequate CCTV system and x-ray source. Magnification to 50X. Target current is 0.4 ua; dark current is extremely low compared with conventional light-sensitive vidicons. Especially suited for non-destructive testing and biological applications.

Typical Operating Conditions

Signal-Electrode Voltage	10 - 30 v
Grid #4 & Grid #3 Voltage	200 - 300 v
Grid #4 Voltage	300 v
Grid #1 Voltage (Picture Cut-off)	45 to 100 v
Highlight Signal-output Current	0.05 - 0.2 ua
Visual Equiv. Signal to Noise Ratio, Approx.	300:1

2″ Vidicon



Only one vidicon has resolution exceeding 2000 TV lines

The new ML-2058G 2-inch diameter TV pickup vidicon is the only vidicon that provides this high detail resolution. Features of the ML-2058G include: 1.4″ diagonal working area; a limiting resolution exceeding 2000 TV lines; 50% amplitude modulation at 1100 TV lines. It is designed for operation with conventional image orthicon deflection coils. Length is 12″. Available with x-ray sensitive photoconductor.

For complete details write The Machlett Laboratories, Inc., Springdale, Conn. An affiliate of Raytheon Co.

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FORCED AIR COOLING
ML-8317

Typical power capabilities:
SSB 100 kW (2 tone)
Plate Mod. RF 125 kW
Pulse Mod. 15 Mw
Max. Anode dissip. 60 kW

VAPOR COOLING
ML-7482

Typical power capabilities:
CW 400 kW
SSB 230 kW (2 tone)
Plate Mod. RF 250 kW
Max. Anode dissip. 200 kW

WATER COOLING
ML-7560

Typical power capabilities:
CW 400 kW
Pulse RF 2.5 Mw
Pulse Mod. 15 Mw
Max. Anode dissip. 175 kW

ALL THREE COOLING OPTIONS use basic, proven electron tube structure: Coaxial, easily cooled terminals; ceramic insulation; thoriated tungsten cathode; heavy wall anode. For technical data write: The Machlett Laboratories, Inc., Springdale, Conn. An affiliate of Raytheon Company.

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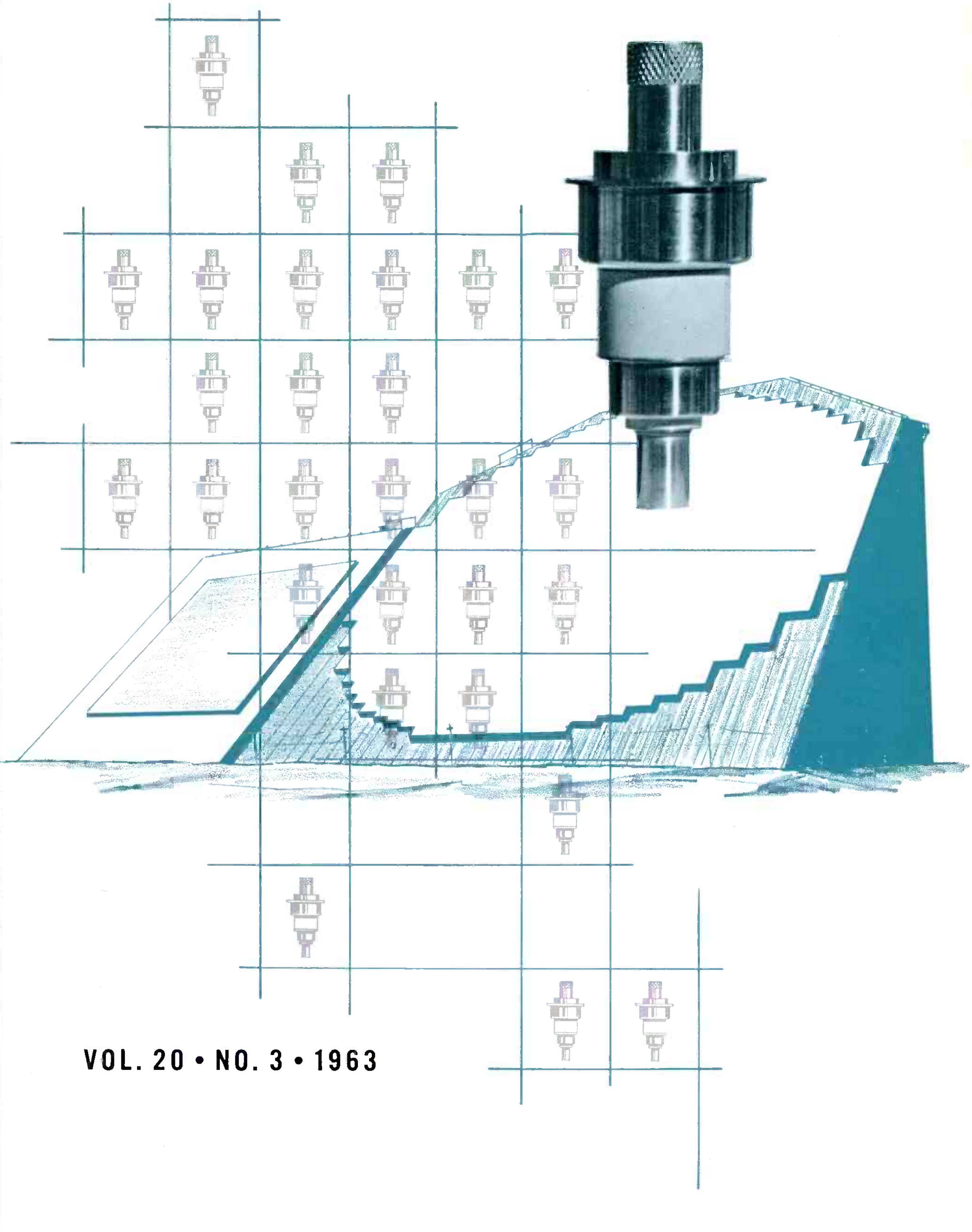

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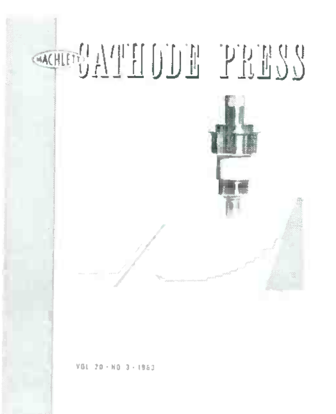

COVER . . . illustrates the U. S. A. F. Phased-Array Space Track Radar at Eglin Air Force Base in northwest Florida. This installation, and the role of the Machlett planar triode in this system, is described in the article starting on Page 2.

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IN THIS ISSUE

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Large Power Tubes

Small Power Tubes

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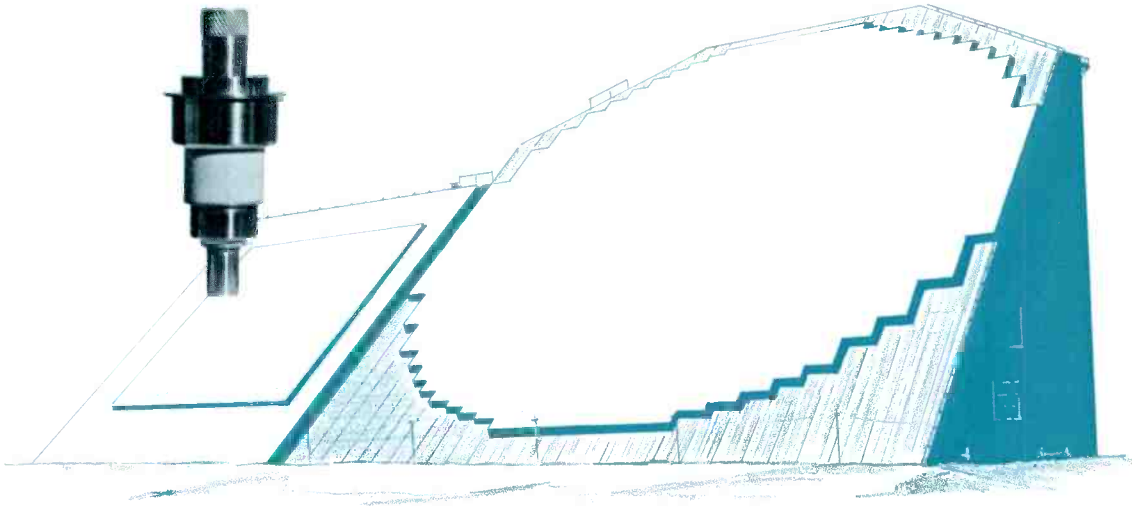


By ALLEN I. SINSKY, Principal Engineer, Bendix Radio Div., The Bendix Corporation

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

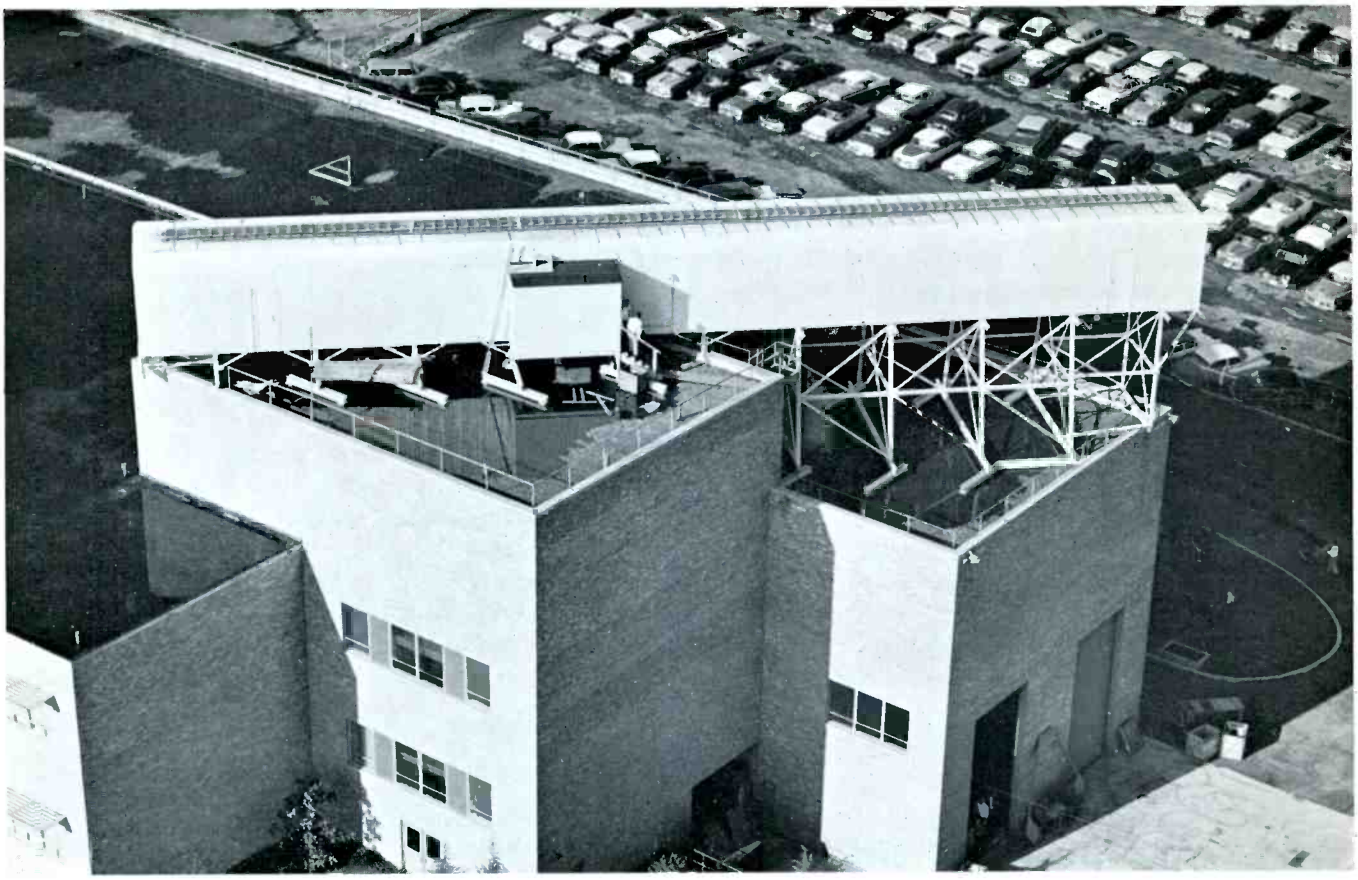


Figure 1 — UHF Linear Array, a complete operating radar, including transmitter, receiver, modulator beam steering circuits and associated controls.

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.

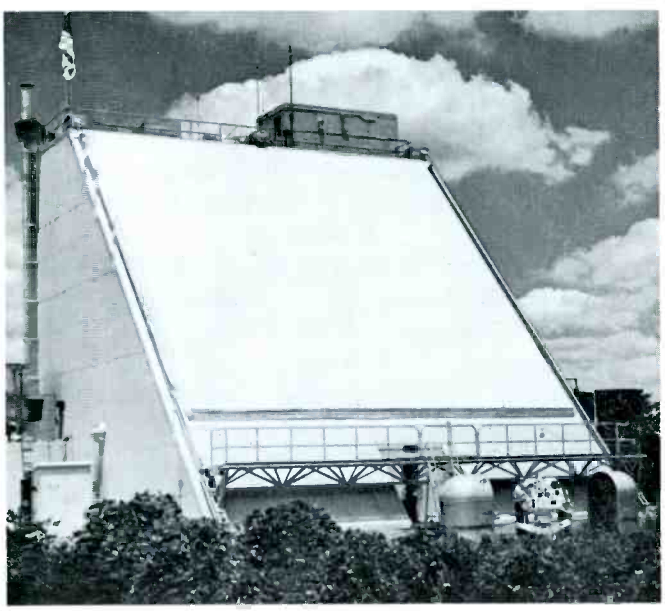
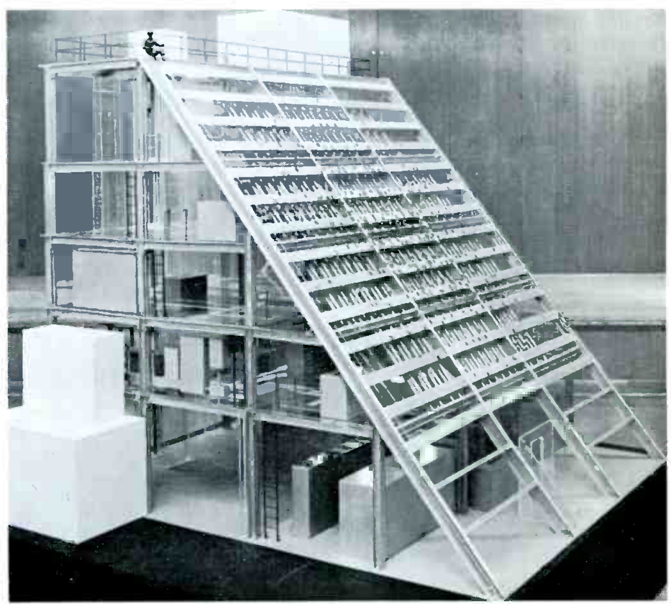


Figure 2B — Scale model of L-band ESAR radar shows equipment location. Air-conditioning of unit provides the constant temperature-humidity necessary to maintain phase control.



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.

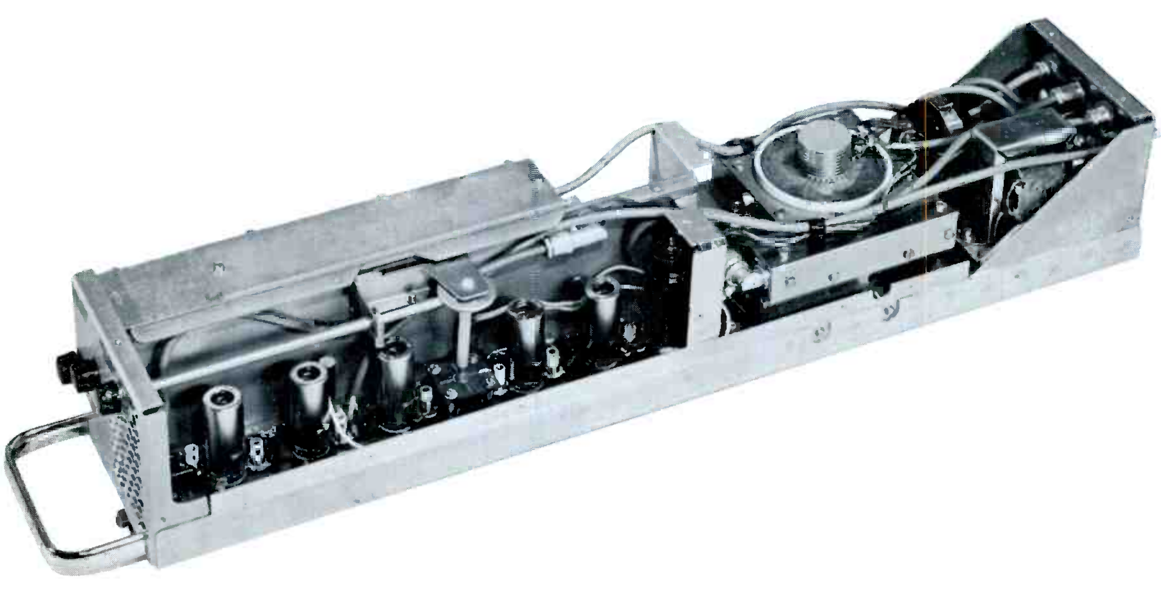
This derating chart combines these three essential upper limits of cathode operation:

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.



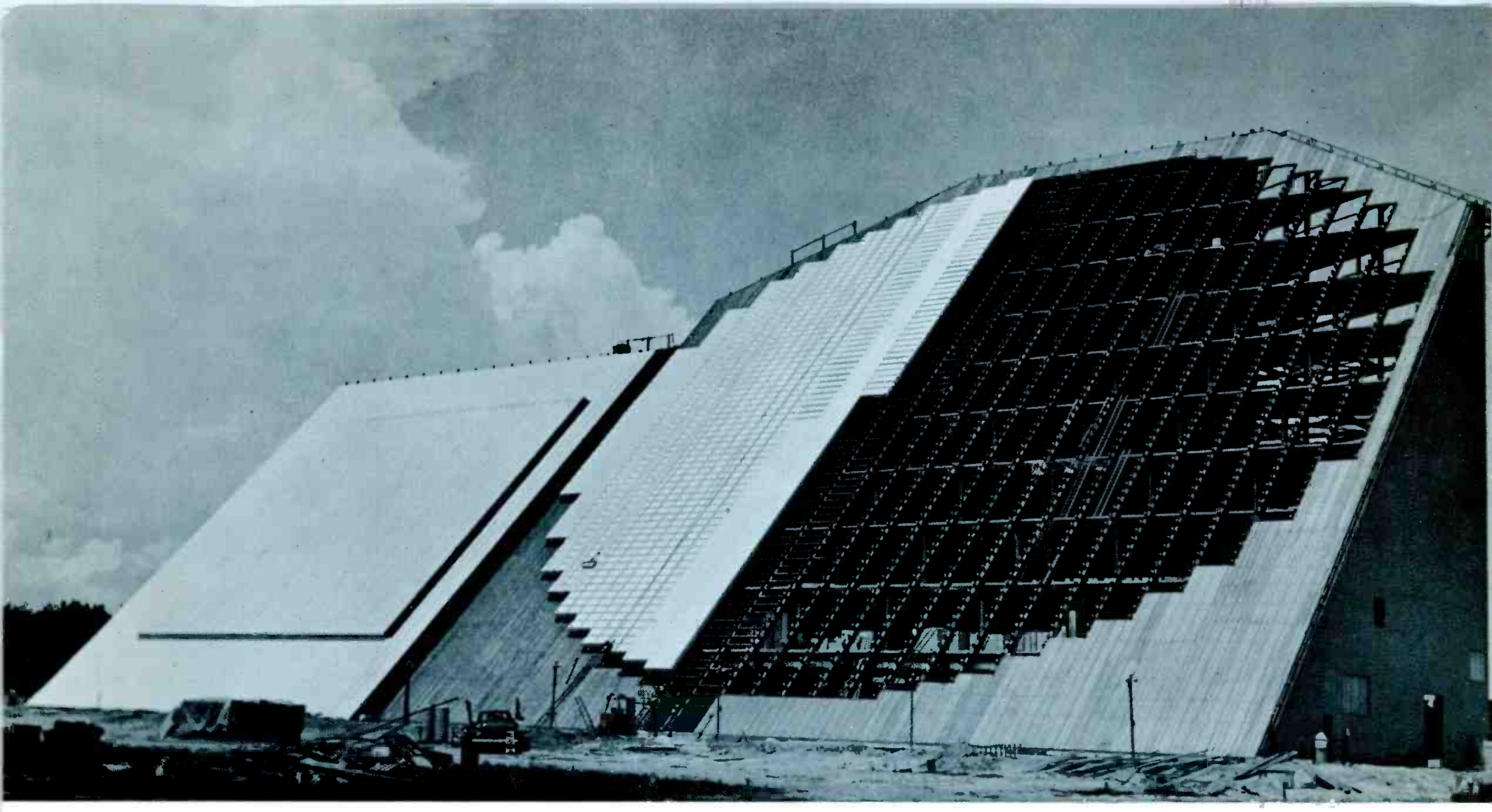


Figure 3 — View of nearly completed AN/FPS-85 Space Track radar at Eglin Air Force Base in northwestern Florida, constructed and installed by Bendix Radio under contract to the U. S. Air Force. This structure stands 150′ high, is 320′ long and 133′ deep at the base. Over 1,600 tons of structural steel 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.

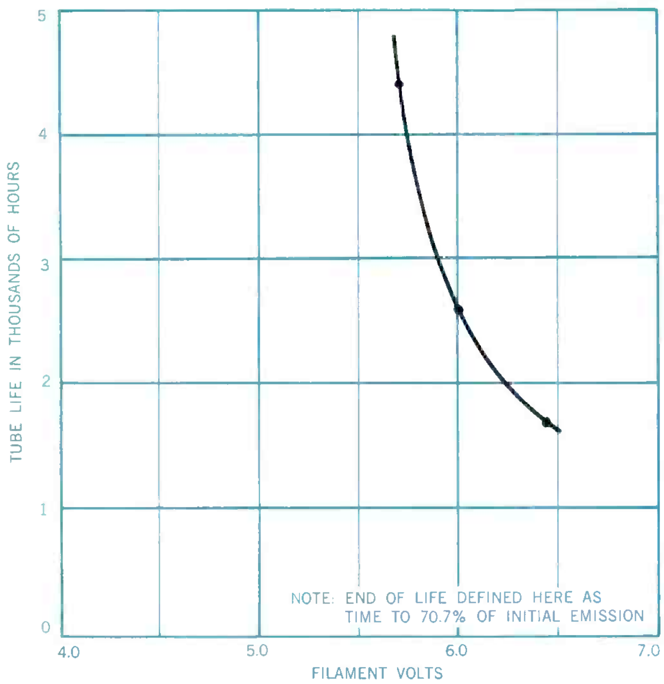
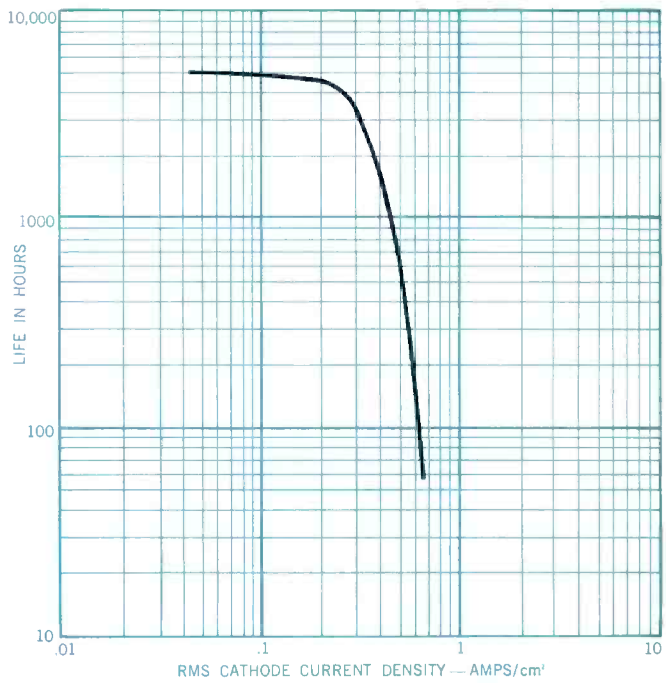


Figure 5 — Cathode Life vs. Current Density for Typical Cathode.



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.

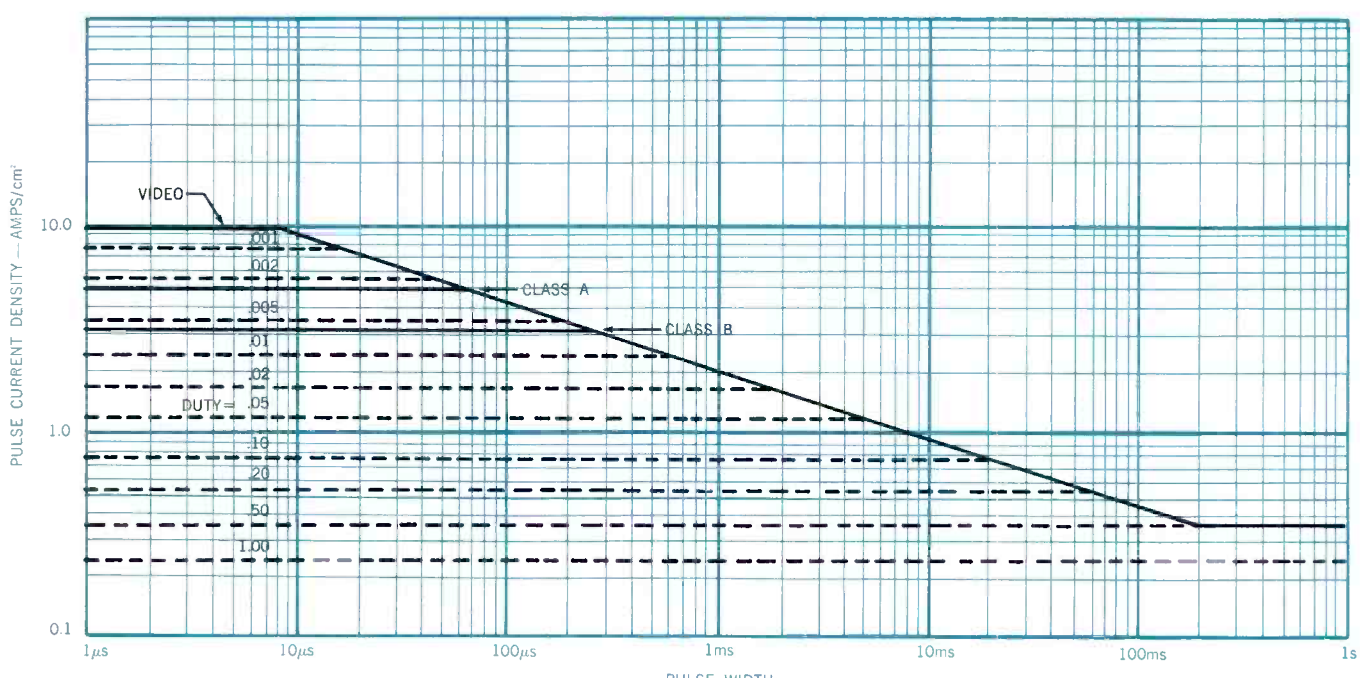
Several interesting points should be noticed in Figure 6. For one thing, no derating is necessary under any conditions to pulsewidths of 10 microseconds and for typical Class A or B operation, no pulse power derating is necessary to pulsewidths of about 100 microseconds. This is considerably at variance 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.

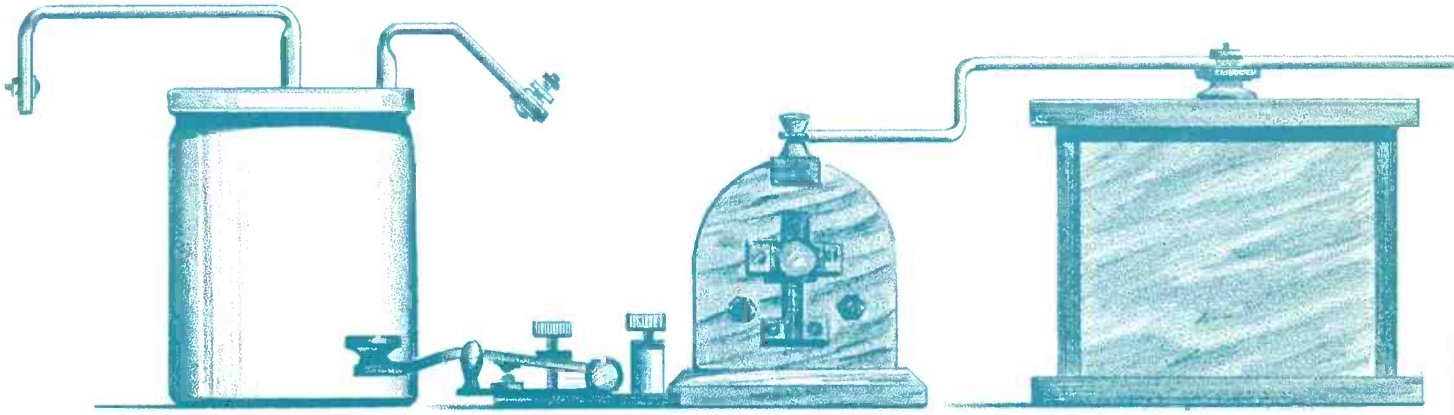
A third interesting point concerns the lower limit of current density below which droop will not occur regardless of pulsewidth. According to the rating curve this occurs at a current density of about 350 milliamps per square centimeter. This current level also determines the pulsewidth at which a tube 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."

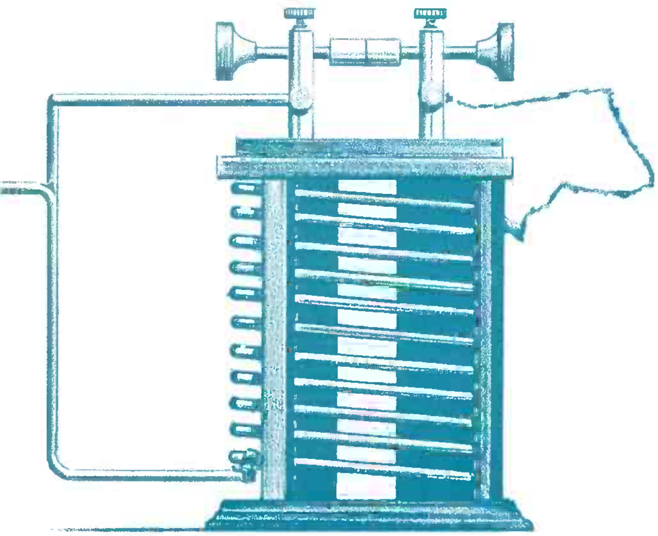
It is thus with special interest that CATHODE PRESS reviews the tube collection and early experiences of Commander Paul G. Watson, USNR (Ret.), whose electronics collection includes not only Geissler tubes and a "pulsed" transmitter of extremely early design (notably simpler than contemporary units)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

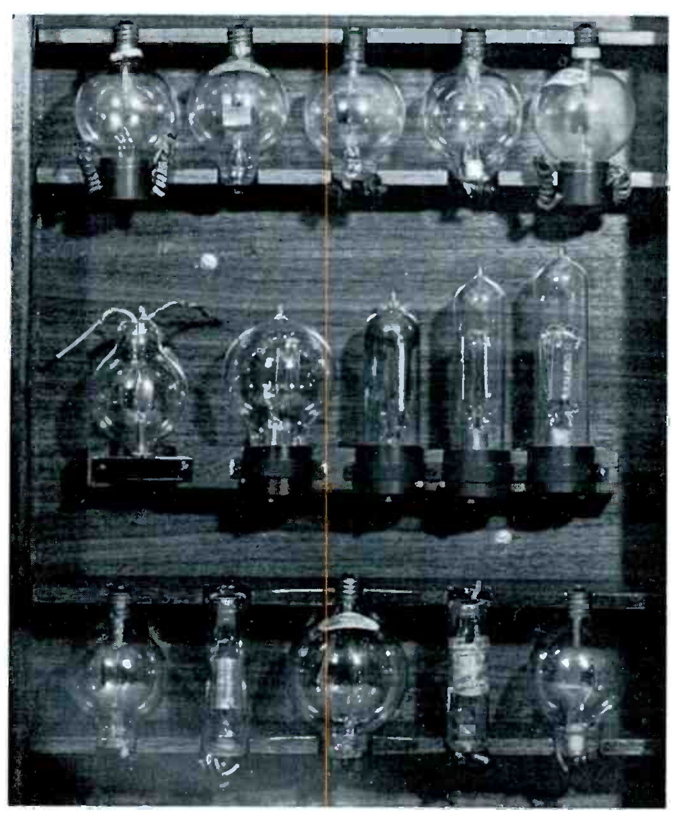
[3]Commander Watson comments that the original deForest triodes were "tubular" and that the spherical tubes (such as the ultra-audion oscillator) were developments of a later date. The suggestion is made, however, that x-ray tube manufacturers were turned to because others' tubes were "too soft." It 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; $3\frac{1}{2}$ 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.

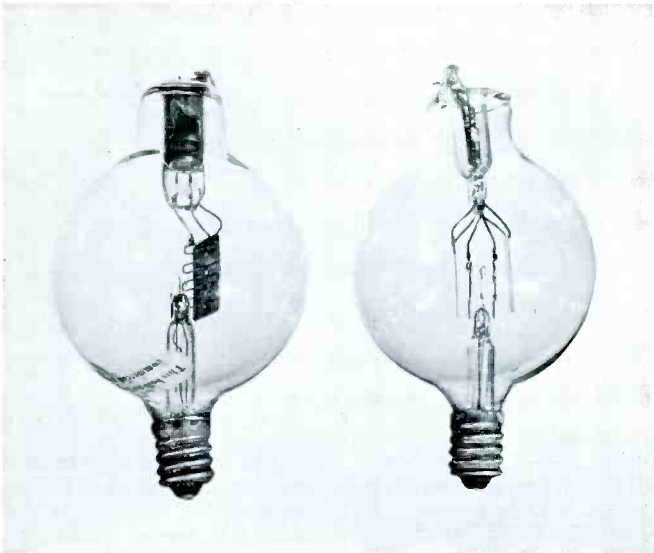


Figure 1a — Enlarged view of third and second tubes, respectively, from left, top row, shown in Figure 1.

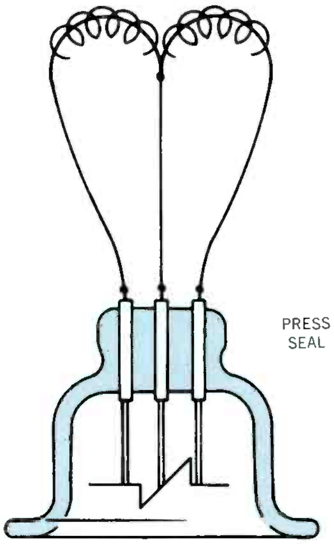


Figure 1b — Sketch illustrating early device (about 1909) to increase emission.

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.

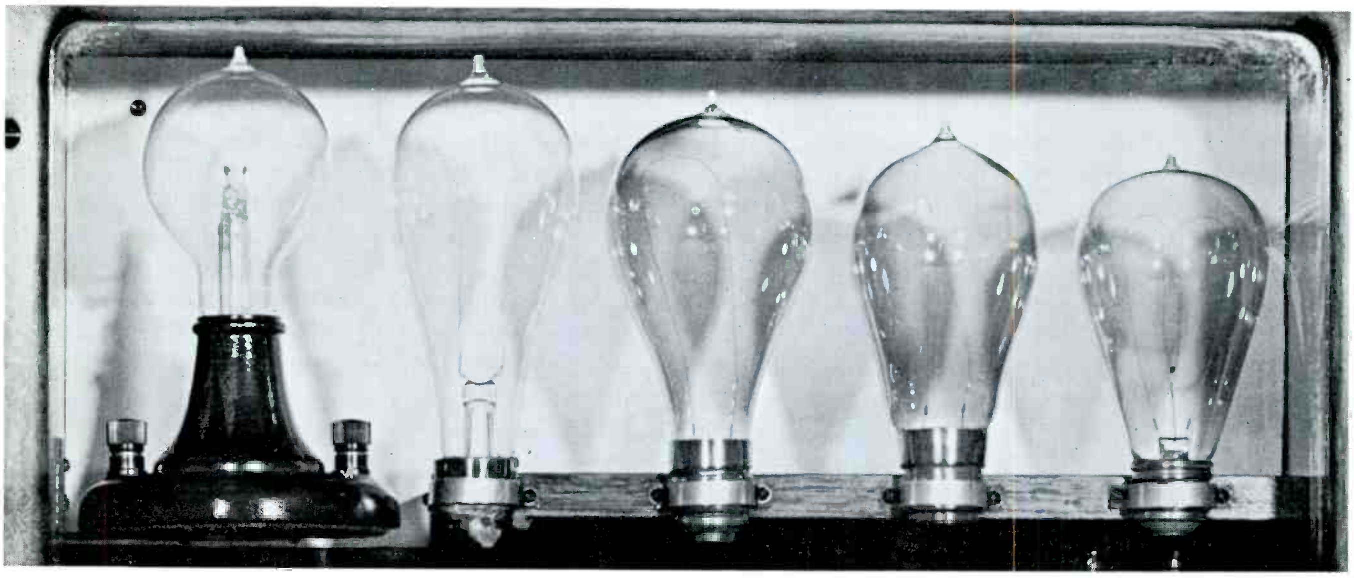


Figure 2 — Lamp "A" is a replica of original Edison bulb made at Nela Park, Cleveland. "B" is an original bamboo filament electric lamp made in Edison "set-up" at Menlo Park, N.J. between 1881 and 1886. Bamboo was coated with asphalt before carburizing to increase strength. "C" is early 1800 "U" filament 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

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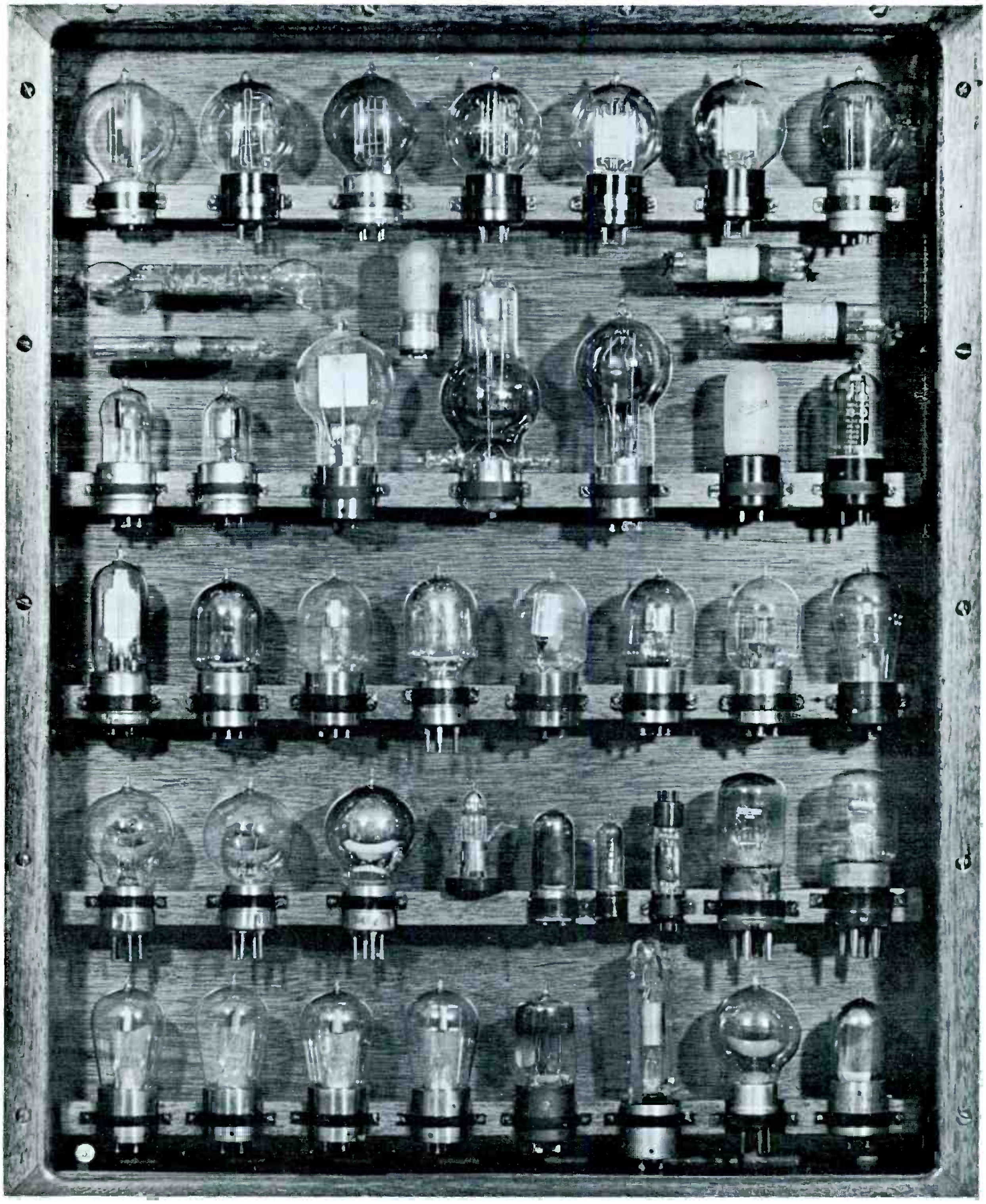
Figure 3 — Top Row: Early W. E. tubes (l. to r.) WE-201-A; 205-D; VT-2; 104-D; 101-F, 102-F; 216-A. The 201-A dates from about 1915, has a 3 button "old Navy" base. The VT-2 (third tube) made for U. S. Government in WW-I was very widely used in 5 watt transmitters. Rest of first row were used as telephone 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.



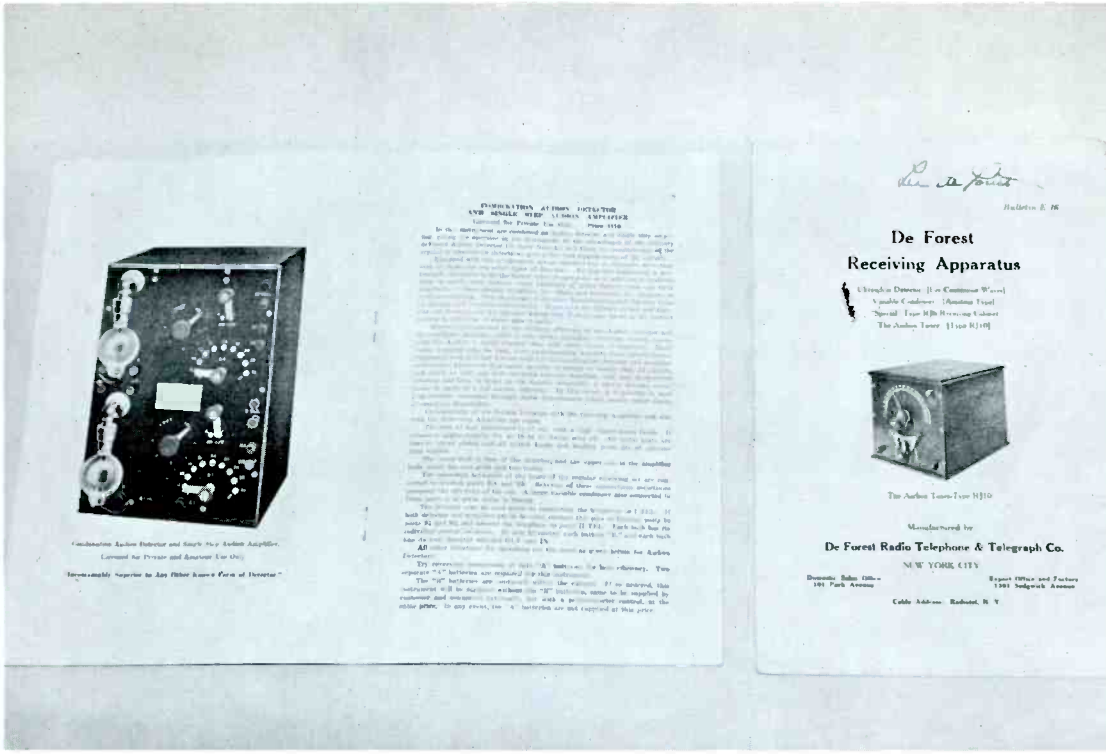


Figure 4 — A reproduction of part of the brochure covering the deForest Audion detector and amplifier, Type RJ 10, for the "higher class of operators." The description which accompanies the RJ 10, which was sold during the period 1909 to 1915, reads:

"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.

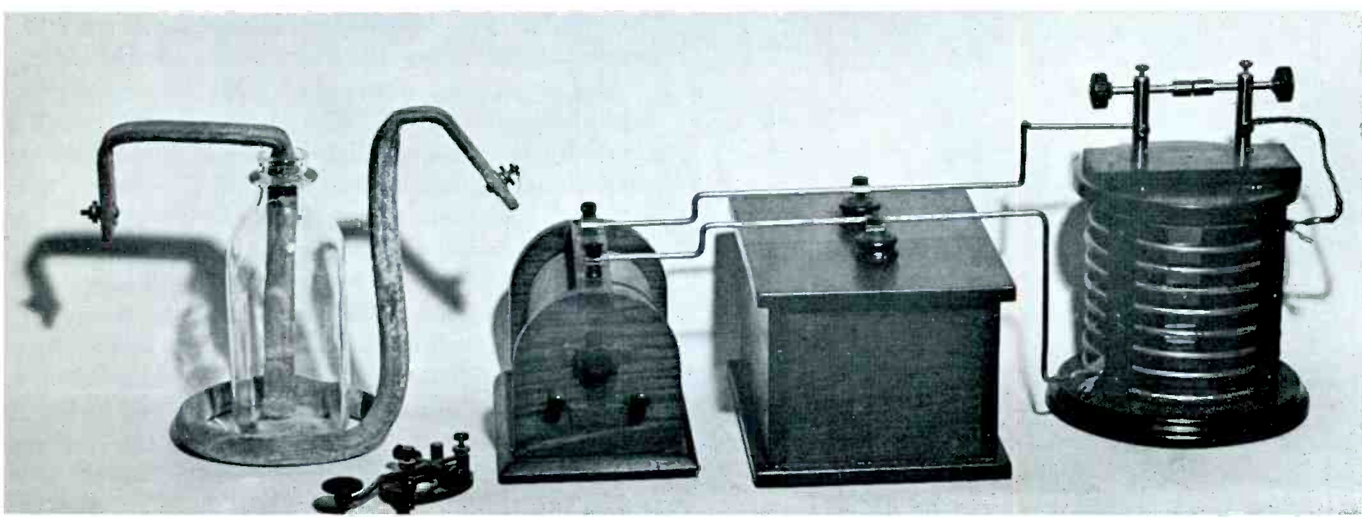
"In 1912 alternating current was available in very few places and certainly not in West Chester. We wanted 'power' and we had power available in the form of 115 volt direct current for house lighting. We had a 'tuned' transmitter now, so during the late summer of 1912 an electrolytic interrupter was 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.



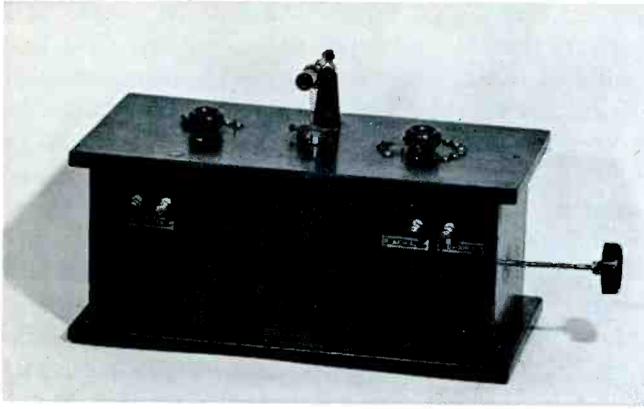


Figure 6 — Station 3BV's receiver. The first model (1910) employed an electrolytic detector. This model, a revised version, employs a crystal detector.

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.

"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.

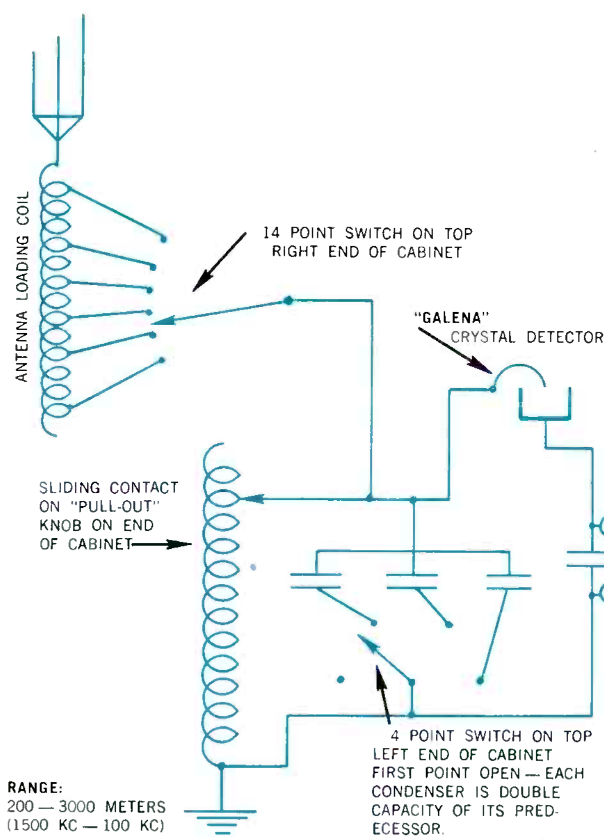


Figure 7 — Schematic drawing of the 3BV receiver.

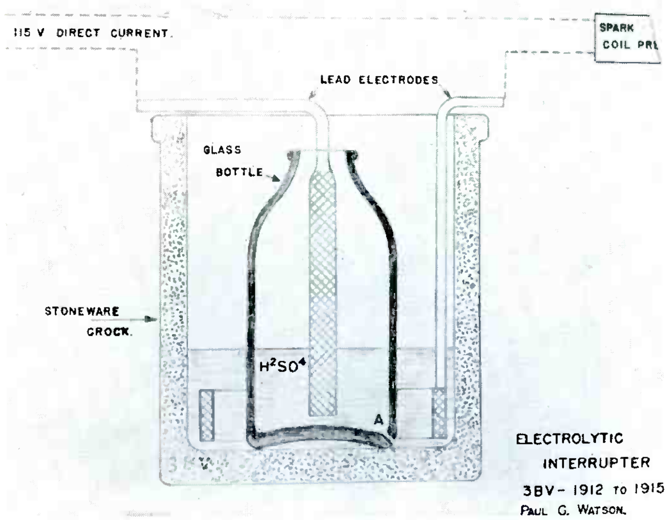


Figure 8 — Schematic drawing of an electrolytic detector of the type first used on 3BV's receiver.

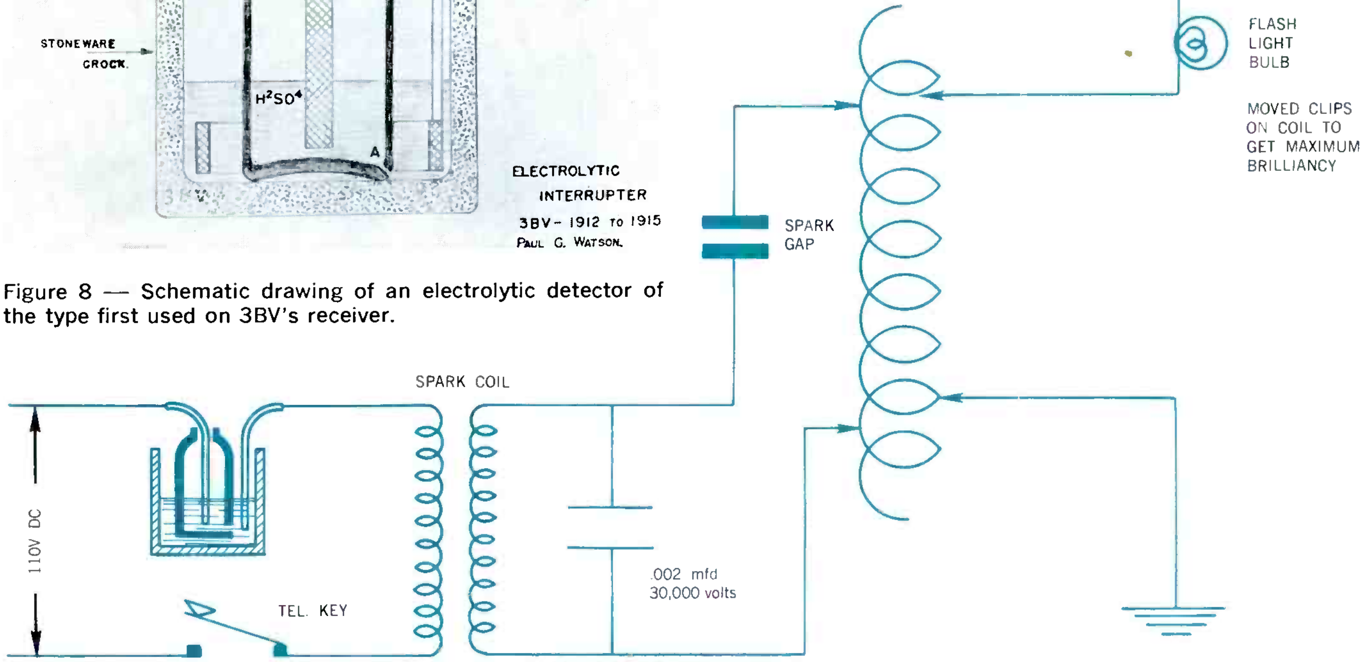


Figure 9 — Schematic drawing of the 3BV transmitter.

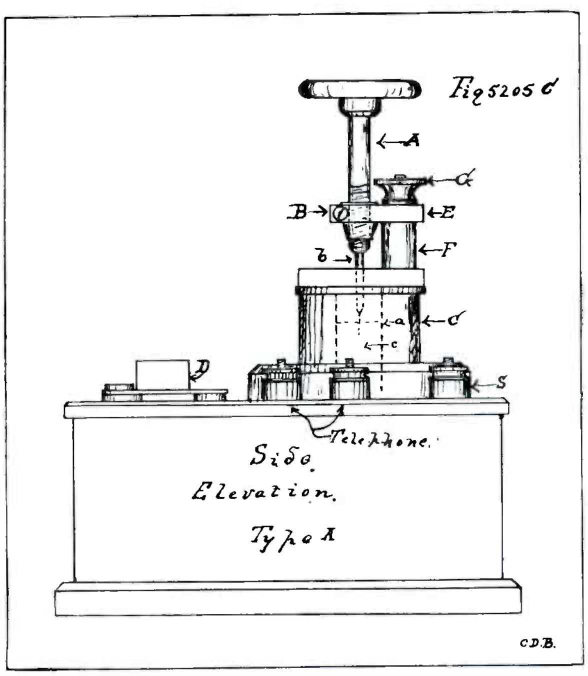
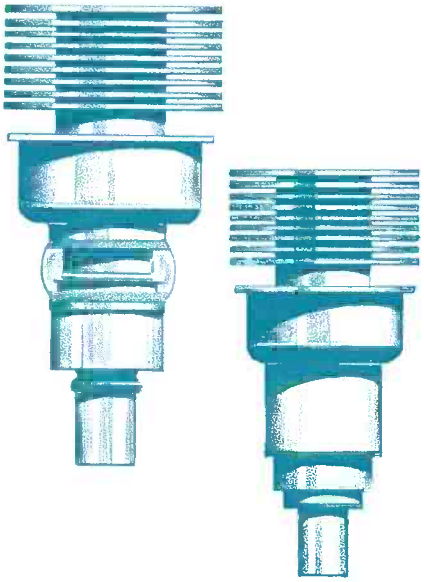


Figure 10 — Drawing of 3BV's electrolytic interrupter or "pulse modulator."

"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

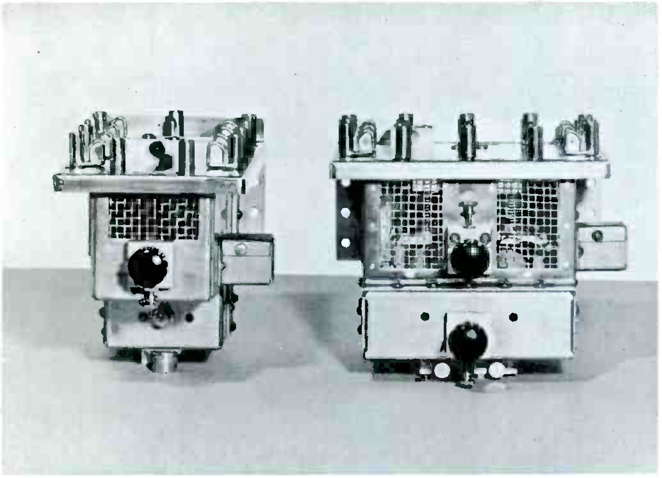


Figure 1 — Tuned line tripler stage (left), tuned line amplifier stage (right) of Translator Models HTU-100 and U-HTU-100.

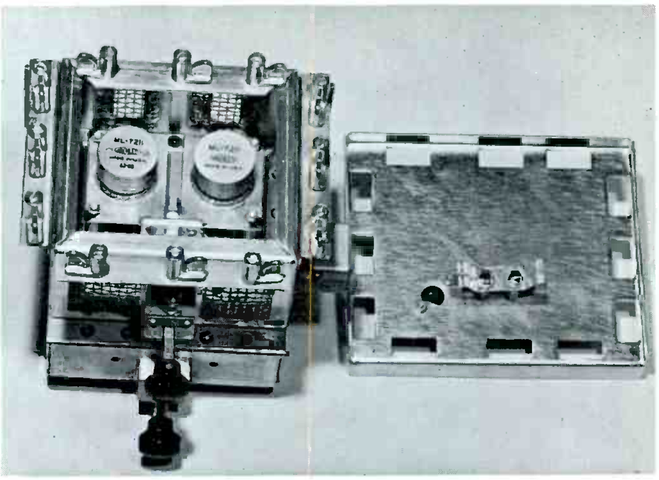


Figure 2 — Individual enclosures to permit maximum tube cooling are employed for the tuned line tripler, mixer and final amplifier stages. The final amplifier stage is illustrated.

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.

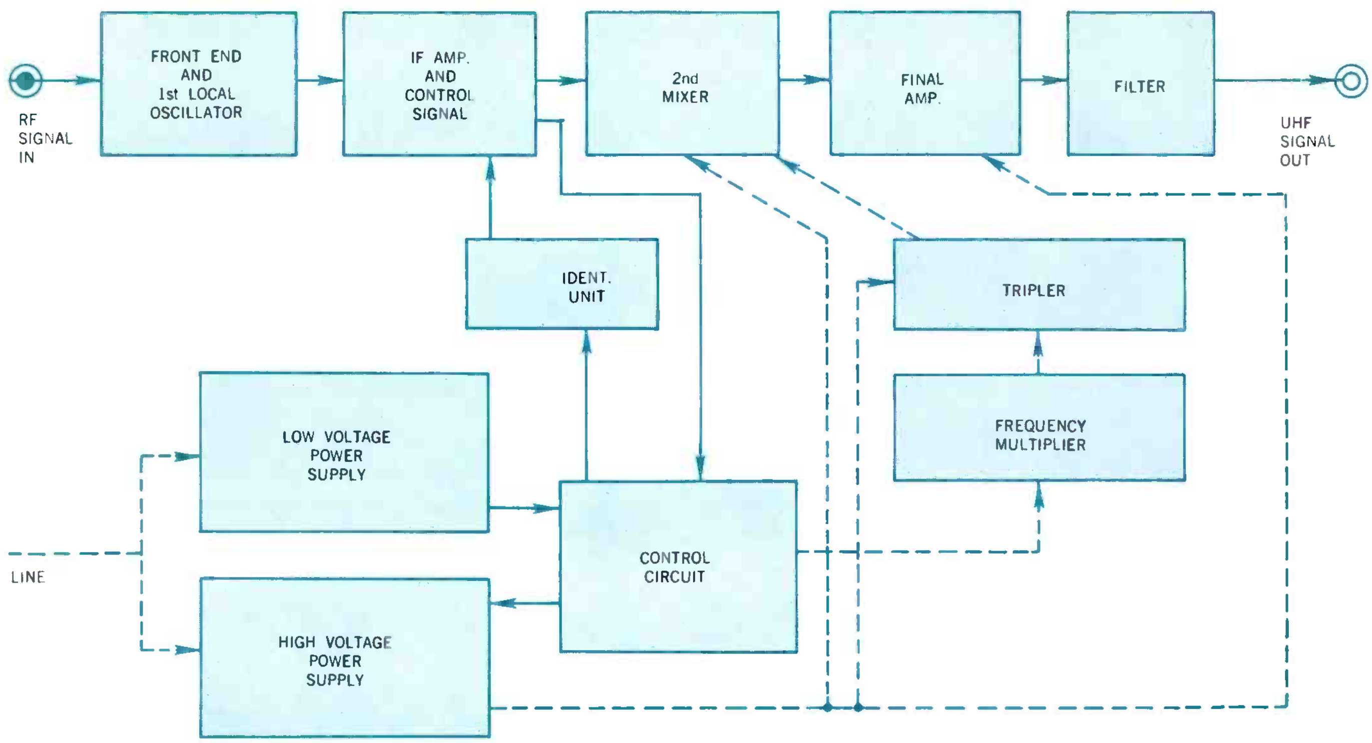


Figure 3 — Block diagram of HTU-100 Translator.

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.

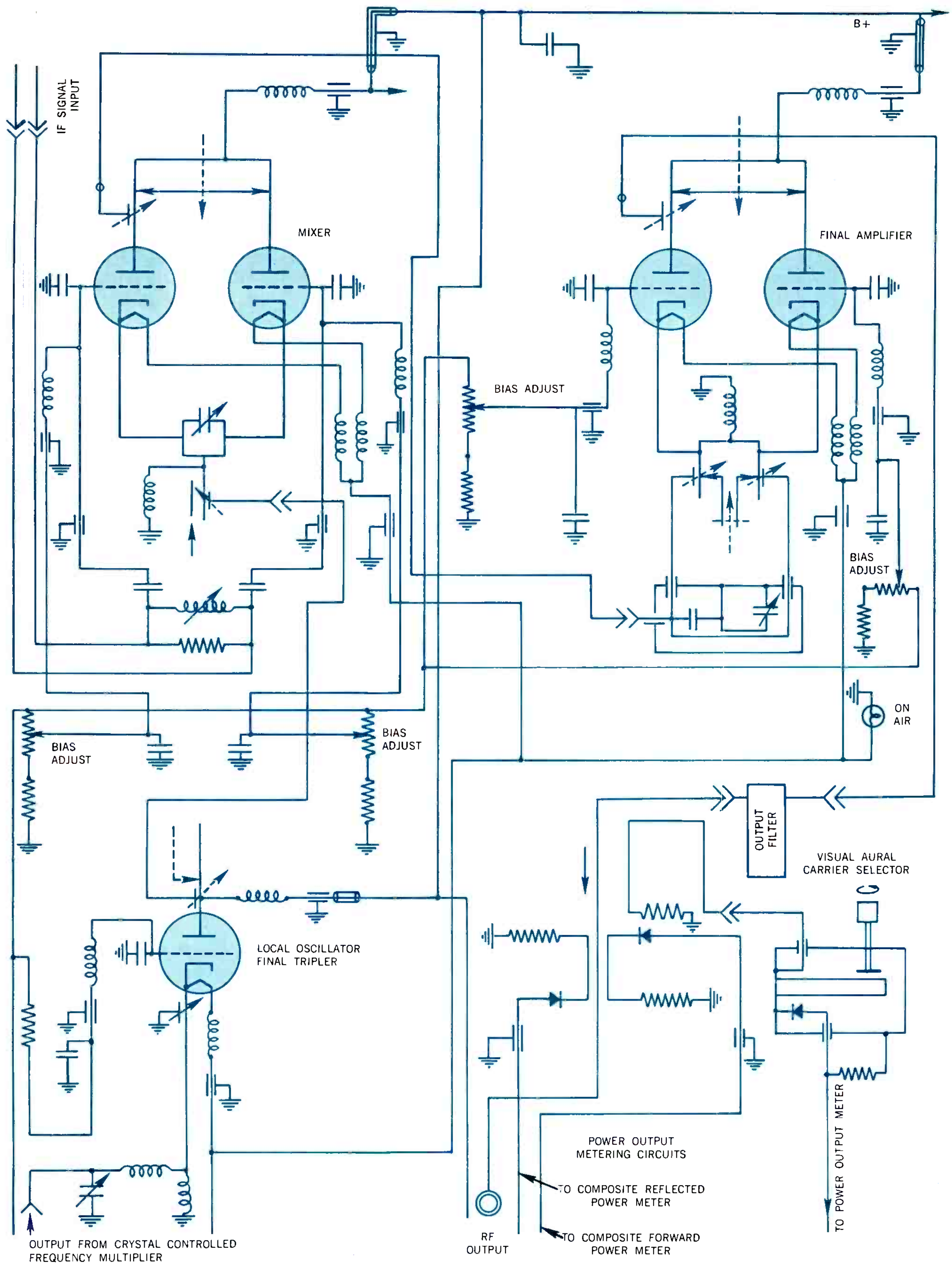


Figure 4 — Circuit detail, mixer, tripler and final amplifier stages.

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

High Voltage Breakdown Problems in High Power Vacuum Tubes

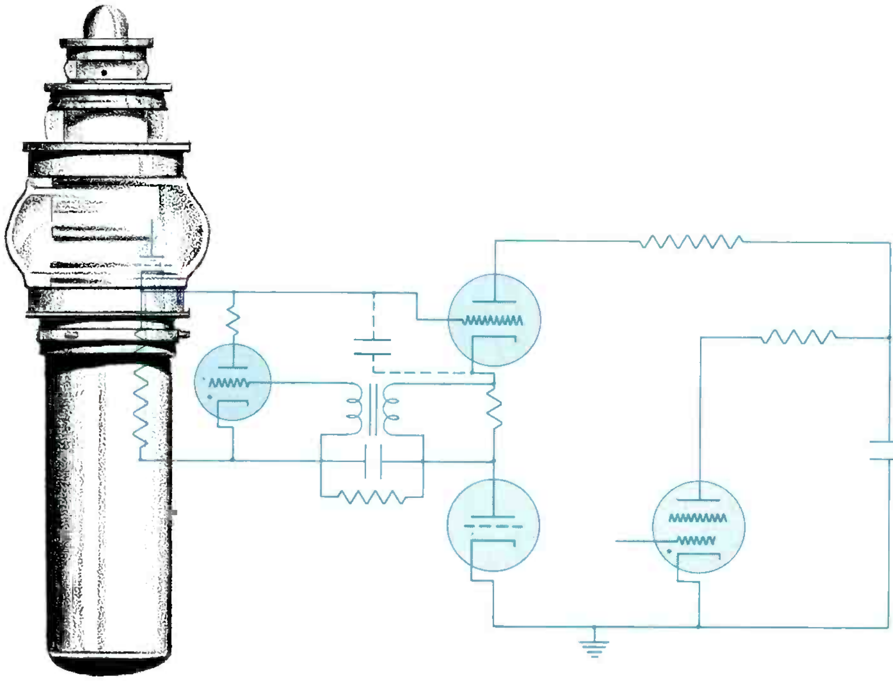
Internal flash arcs in power tubes date from the first use of high power communication transmitters at Rocky Point, Long Island. This phenomenon came to be known as the "Rocky Point" effect and has been discussed in various papers. Improved processing of tubes and better tube design have resulted in 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.

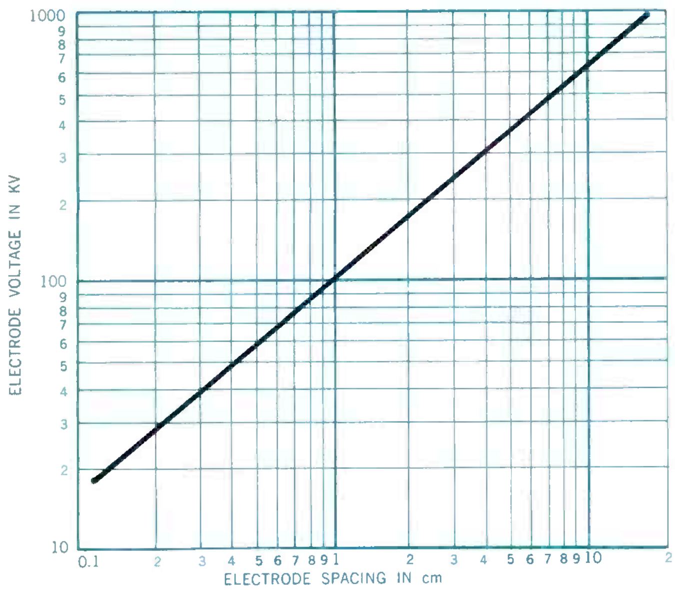


Figure 1 — Maximum "spark-free" potential differences between two parallel plan electrodes in vacuum as a function of their spacing. (Kilpatrick, **Rev. Sci. Instr.**, Oct. 1957).

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

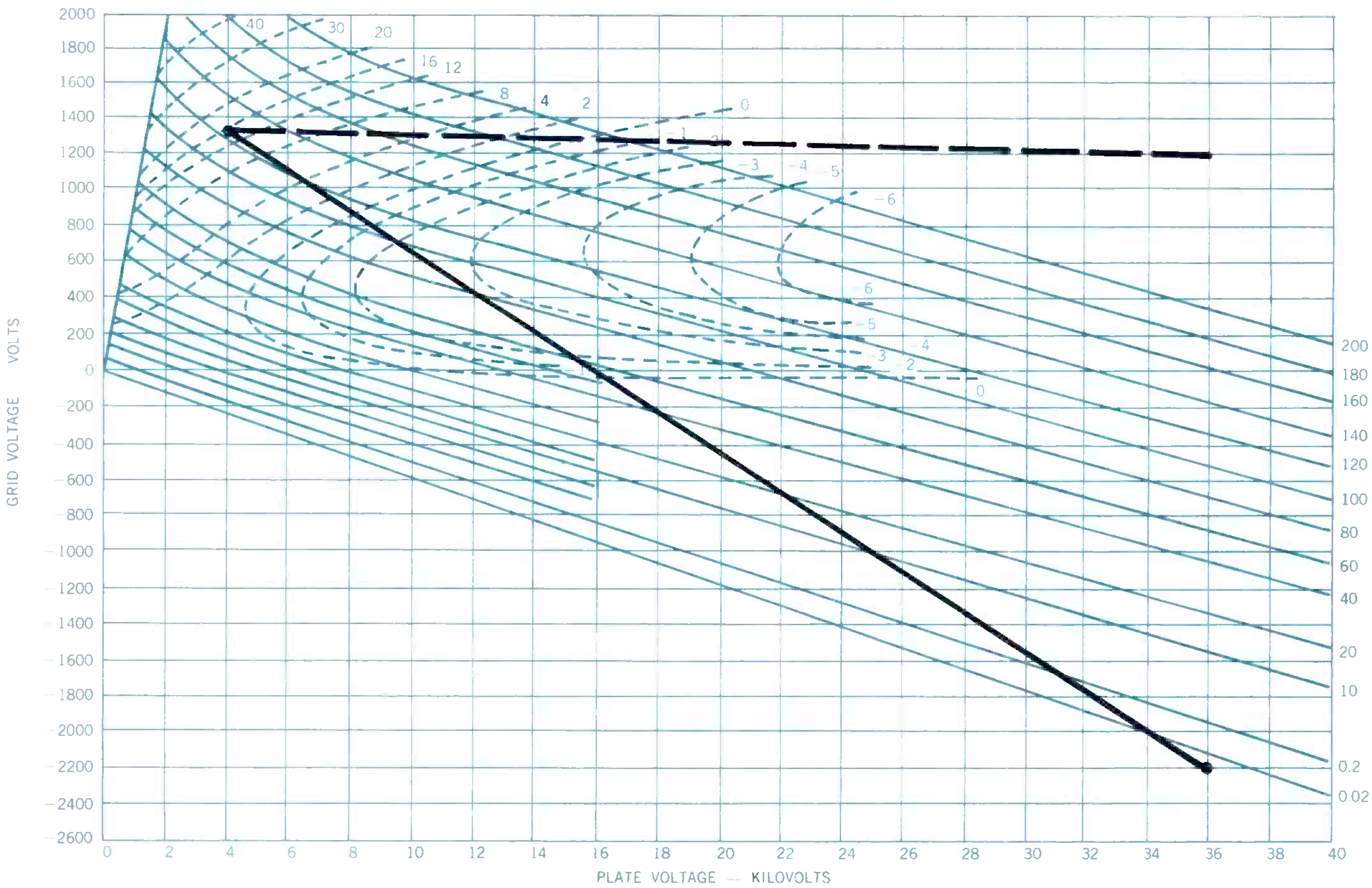


Figure 2 — ML-6696 Constant Current Characteristics showing normal load line as solid line, and load line when load arcs as dotted line.

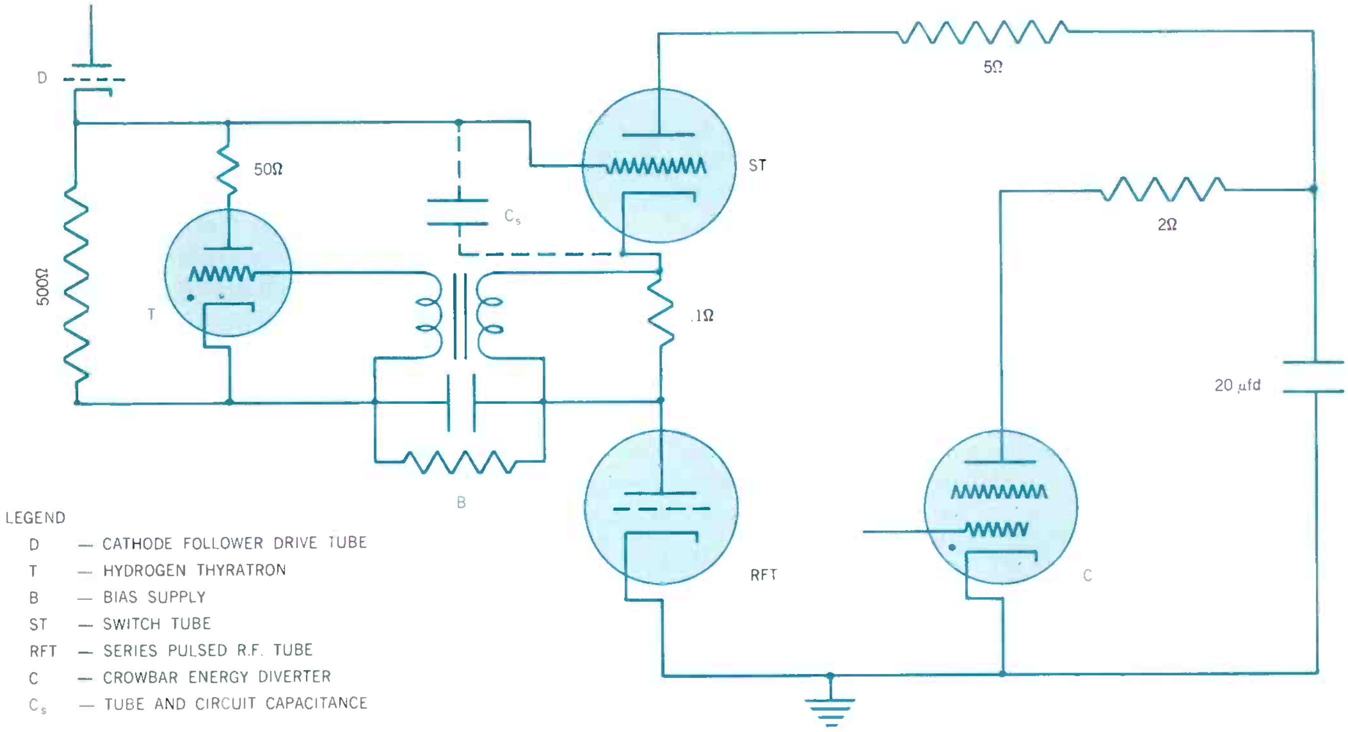


Figure 3 — Circuit showing a thyratron in a switch tube grid circuit. The switch tube is cut off when load tube arcs by firing the thyratron, T, by voltage developed across 0.1 ohm resistor.

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

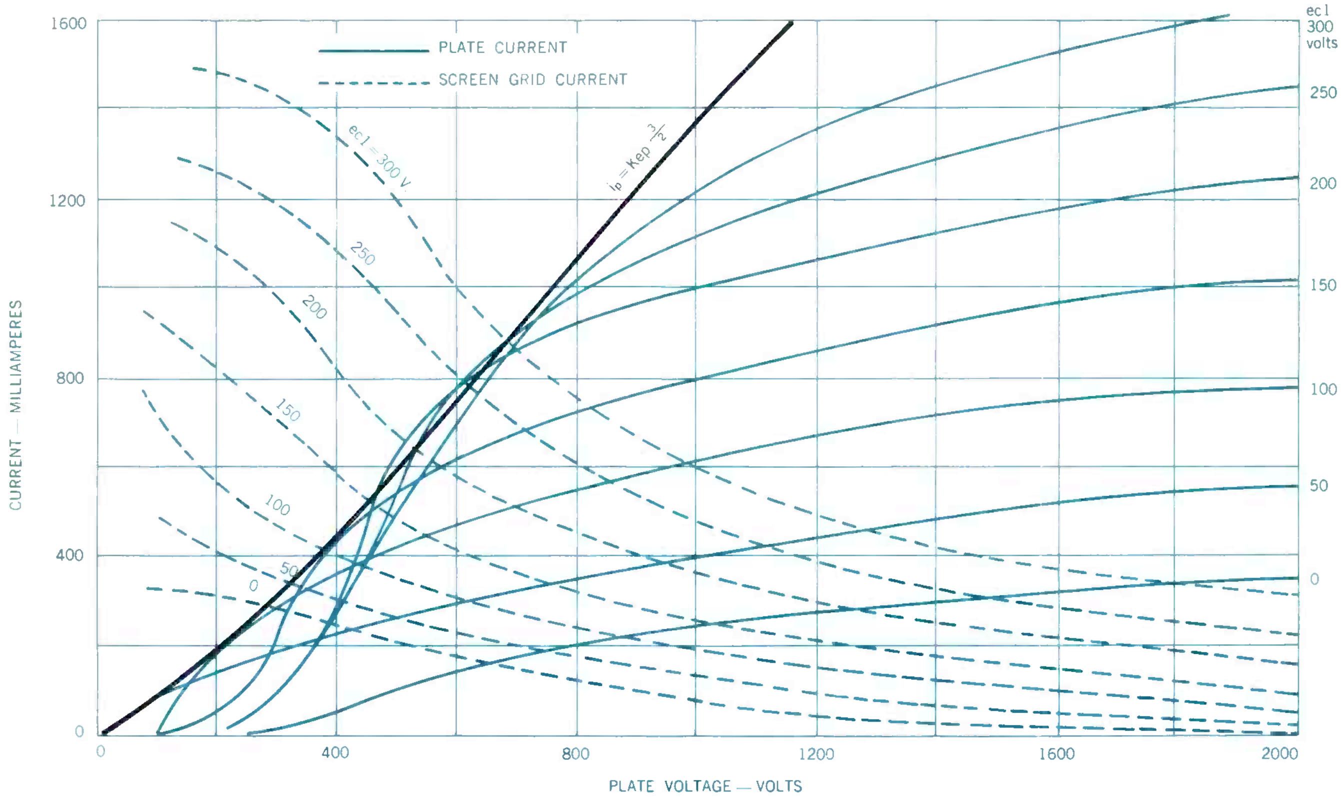


Figure 4 — Typical Constant Grid Voltage Characteristics. Line labelled $i_p = Kep^{3/2}$ shows plate current drawn from virtual cathode formed between screen grid and plate.

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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UNIQUE MACHLETT DP-30 FOR... SWITCH TUBE OR PULSE AMPLIFIER

as switch tube:		as pulse amplifier:
30kw switch	**OR**	20kw peak pulse
at 0.0033 d		at 1Gc

The unique DP-30 planar triode does double duty as an rf pulse amplifier (or oscillator), or modulator/switch tube. Typical performance as an rf amplifier: 20kw peak pulse power at 1Gc, 0.001 d. Typical performance as a switch tube: 5a x 6kv for 30kw switch power at 0.0033d. ■ For data write: The Machlett Laboratories, Inc., Springdale, Connecticut. An affiliate of Raytheon Company.

MACHLETT

ELECTRON TUBE SPECIALIST

[MACHLETT UHF PLANAR TRIODES]

demonstrated reliability in Mariner II and Mercury programs...accepted for Ranger and Nimbus.

HERE'S WHY:

Phormat Cathode: High voltage stability for grid or plate pulsed applications. Phormat (matrix) cathodes have been tested to 12,000 volts and more. Used in planar triodes ML-7211, ML-7698, ML-7815, ML-8403, and DP-30.

Frequency Stable Anode: Unique anode design allows frequency stable operation within 10-15 seconds after application of high voltage, plus these advantages:

1. Frequency shift during initial tune-up less than 1 Mc.
2. Does not require regulated plate supply, since change of anode dissipation does not affect frequency.
3. Permits variable duty cycle without noticeable shift in frequency.

Used in planar triodes ML-7855, ML-8403, ML-518.

High Cathode Current: 50% more cathode current (190 vs. 125ma) permits power to 110 watts CW. Used in planar triodes ML-7211, ML-8403.

Pulsed Operation: High voltage stability—phormat cathode provide reliable pulsed service (see table).

SPECIFICATIONS OF PULSED MACHLETT PLANAR TRIODES

Tube Type	Max f	Plate Pulsed Max Pulse Power input	Max f	Grid Pulsed Max Pulsed Power input
ML-6442	5Gc	3000 v eb 2.5 a ib	—	—
ML-6771	6Gc	3000 v eb 1.5 a ib	—	—
ML-7209[1]	3Gc	3500 v eb 3.0 a ib	—	—
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
ML-8403[3, 5]	3Gc	3500 v eb 5.0 a ib	3Gc	2000 Vdc Eb 5.0 a ib
DP-30	Pulse Modulator DC Plate Volts 8 kv	Pulse Cathode Current 5.0 a ib		

1. High shock rating. 2. 12 second warm-up. 3. High cathode current; Phormat cathode. 4. Phormat cathode. 5. Frequency stable anode.

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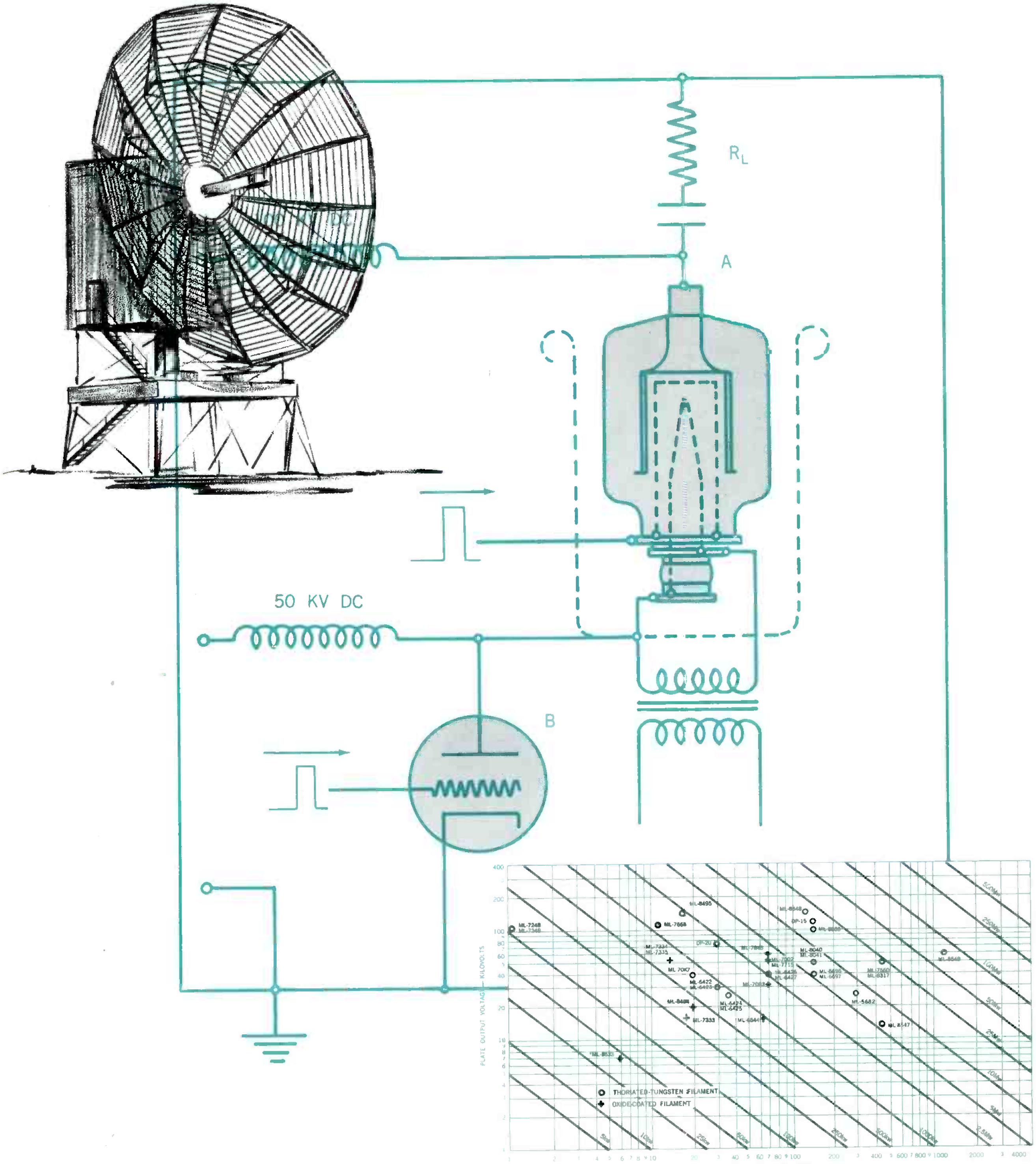

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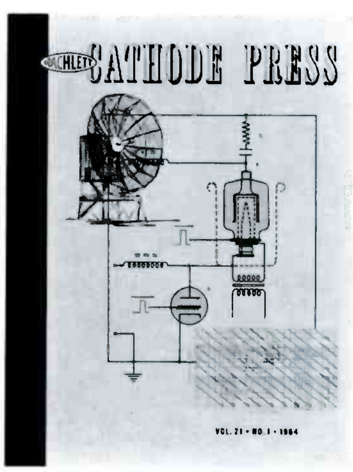

COVER . . . is a representation of the design and application aspects of pulse tubes for high voltage, high power video and rf pulsing. Part I of a two-part article on this subject begins on Page 2.

CATHODE PRESS

Vol. 21, No. 1, 1964

Editor, *Richard N. Rose*

Art Director, *Edward J. Bulger*

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Small Power Tubes
Photosensitive Tubes

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Editor's Note:

This is Part I of a two-part article which is an unusually complete compilation of design and application data on this subject. Part II, "Interactions Between Pulse Modulation Tubes and Circuits" is scheduled for CATHODE PRESS, Vol. 21, No. 3. Both parts are to be reprinted in Machlett's brochure "Pulse Tubes for High Voltage, High Power Video and RF Pulsing" (1964 Edition).

Vacuum Power Tubes for Pulse Modulation

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Part 1

Design, Theory and

The generation of high voltage and/or high power pulses is essential for most radar or other applications involving pulses of electromagnetic energy. The generation of power pulses requires an electrical energy storage element which can be either a capacitor or an inductance. For practical reasons a capacitor is nearly always used. In order to transfer the energy from the storage device to the pulse energy generator, some type of switch is required. Gaseous devices such as thyratrons, ignitrons or spark gaps may be used. Similarly vacuum tubes may be used. The principle difference in these two types of control devices is that the gaseous devices are capable of being turned on only, whereas vacuum tubes allow complete control over the transfer of energy. Gas tubes are used extensively with pulse forming networks to generate high power pulses. Whenever pulses must be spaced close together, or the pulse shape must be carefully controlled, hard tubes, i.e., high vacuum tubes, must be used.

Since Class C operation of transmitting tubes is quite similar to a high duty cycle pulse modulator, power transmitter tubes can easily be applied to pulse generation. In more recent years vacuum tubes have been designed especially for pulse operation.

The principle design features for tubes to be used in pulser operation are high voltage stability, high output current, good efficiency and precise control of the output power. The transition from the non-conducting to the conducting state must be accomplished in a time short compared to the pulse width. These various factors will be discussed in the following paragraphs.

Principal Design Factors of High Vacuum Pulse Modulator Tubes

1. The basic equations governing the flow of current.

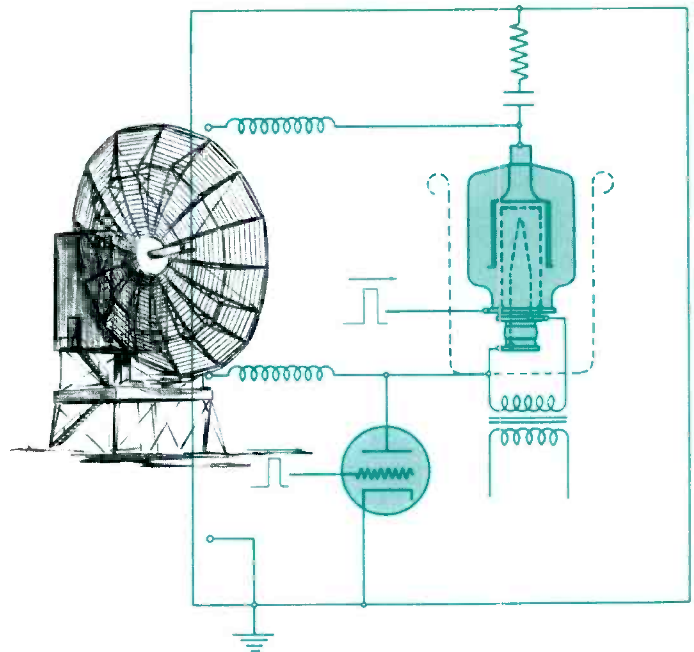
All vacuum tube cathodes emit-space-charge limited current according to the formula:

$$i_k = i_p + i_g + i_{sg} = \frac{2.33 \times 10^{-6}\,\alpha A}{S^2}\left(e_g + \frac{E_{sg}}{\mu_{sg}} + \frac{e_p}{\mu_p}\right)^n \quad (1)$$

where i_k = instantaneous cathode current in ma
i_p = instantaneous plate current in ma
i_g = instantaneous grid current in ma
i_{sg} = instantaneous screen-grid current in ma
α = a constant dependent on geometry of tube
A = cathode emitting area in cm^2
S = equivalent diode spacing in cm
e_p = instantaneous plate voltage in volts
E_{sg} = dc screen-grid voltage in volts
e_g = instantaneous control-grid voltage in volts
μ_p = plate amplification factor
μ_{sg} = screen-grid amplification
n = very nearly 3/2 for most geometries

Instantaneous values are given for currents and voltages because it is not possible to take dc readings in the positive grid region due to problems of electrode dissipation. The screen voltage is given as dc since that is the usual operating condition.

For a simple planar electrode triode this formula reduces to:



Operational Characteristics

$$i_k = i_p + i_g = \frac{2.33 \times 10^{-6} A}{S^2}\left(\frac{e_p}{\mu_p} + e_g\right)^{3/2} \qquad (2)$$

where A is the actual cathode area, S is approximately the grid-cathode spacing, e_p and e_g are the plate and grid voltages and μ_p is the amplification factor. The basic definition of the amplification factor is given by the ratio of the active grid to cathode capacitance to the plate to cathode capacitance. These capacitances refer only to that portion of the cathode structure which is emitting; i.e., the passive or tube structure capacitances are not to be included in the above ratio. Obviously, for a given grid-cathode spacing, μ_p increases as the plate to grid distance increases and it decreases if the grid wire mesh or helix is more open. μ_p is not affected by the grid cathode spacing in a well designed tube.

For a cylindrical triode like the conventional radio transmitting tube using thoriated-tungsten wires in a birdcage structure (See Figure 1), it is not possible to achieve a precise formula for i_k. However, equations which are accurate to a few per cent can be used. The form is essentially the same as for a planar triode:

$$i_k = i_p + i_g = \frac{2.33 \times 10^{-6} \alpha A}{S^2}\left(\frac{e_p}{\mu_p} + e_g\right)^{3/2} \qquad (3)$$

where α is a constant depending on the spacing between cathode and grid, the diameter of the cathode wires and the spacing between cathode wires, A is the cathode emitting area and S is the equivalent diode spacing. The latter is about 10% to 20% greater than the actual grid-cathode spacing. α is unity for solid cylindrical cathodes when $S <<$ cathode diameter. α is between 2 and 10 for most cathodes consisting of a number of parallel wires spaced many wire diameters apart.

In addition to the above equations, one needs a formula to calculate the division of current between the plate and the grid for various electrode potentials. Again no exact expression can be found. Approximate formulas are available. The simplest expression which gives fair results for $e_p/e_g > 2$, i.e., where anode current is less than j_o in equation 5, is given by:[1,2]

$$\frac{i_p}{i_g} = \delta\sqrt{\frac{e_p}{e_g}} \qquad (4)$$

where δ is a constant depending on the interelectrode spacings and the screening fraction of the grid.

Another equation which is vital to tube design is that giving the maximum current which can cross the space from grid to anode in triodes or the screen grid to anode in tetrodes. This current is limited by the total space charge in the grid-anode or screen-grid-anode region and accounts for the high grid current and low plate current at low plate voltages seen on the characteristic curves of all tube types. This maximum current[3,4,5] in ma. per square centimeter of the active anode surface, j_o, for triodes is given by the equation:

$$j_o = \frac{2.33 \times 10^{-6}\,(e_p^{1/2} + e_g^{1/2})^3}{d^2} \qquad (5)$$

where e_g is replaced by E_{sg} for tetrodes
d = grid or screen-grid to anode spacing in centimeters

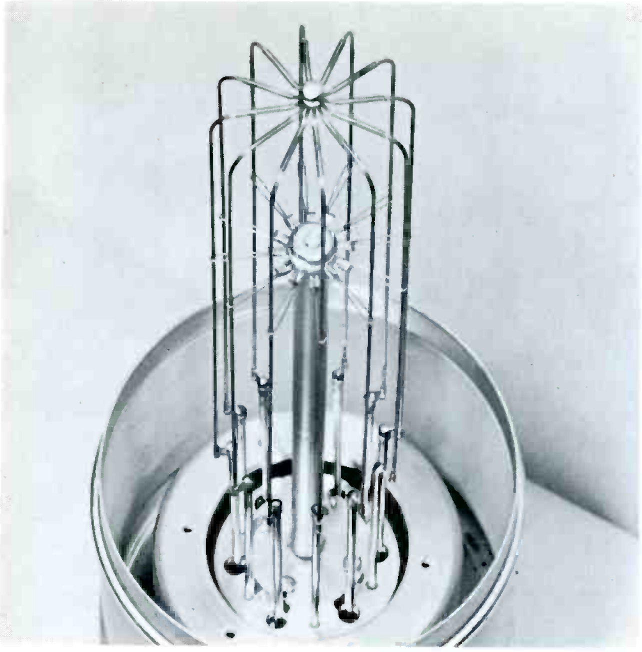


Figure 1 — A typical thoriated tungsten wire cathode — cathode of ML-7480 above.

Equation 3 for the total cathode current in a triode can be simplified to

$$i_k = i_p + i_g = K\left(\frac{e_p}{\mu_p} + e_g\right)^{3/2} \qquad (6)$$

where K is a constant called the perveance, which is dependent on the total cathode emitting area, the form of the cathode, and the grid-cathode spacing. For high perveance the cathode area must be as large as possible and the grid-cathode spacing must be as small as is feasible. Typical values of K vary from 1 microperve or one microampere per volt 3/2 for a gun of a klystron transmitting tube to 10,000 microperves or 10 milliamperes per volt 3/2 for a large radio transmitting tube. Even in the latter case, it is easy to see that e_g must be driven of the order of 2000 volts positive in order to get a few hundred amperes of emission current from a cathode. This is so since e_p must be small during conduction of current, i.e., the tube drop must be low. Figure 2 shows the effect of grid-cathode spacing on the effective drive voltage $\frac{E_{sg}}{\mu_{sg}} + \frac{e_p}{\mu_p} + e_g$ for tetrodes. For triodes the same data can be used but $E_{sg} = 0$. (As noted above $\frac{e_p}{\mu_p}$ is usually negligible in either case). Figure 2 also shows that the effective grid drive voltage must be increased in order to draw higher emission current density from the cathode.

The numerical value of perveance depends on grid-cathode spacing, cathode area and also on the form of the cathode. A squirrel-cage type of cathode of a length, L, with 16 wires on a two-inch bolt circle spaced a distance, S, from a grid will have a certain perveance. Doubling the number of cathode wires on the same bolt circle will raise the perveance by only 30%, but require twice as much cathode heating power. A cylindrical cathode of sheet metal 2-inches in diameter and the same length will have only about twice the perveance of the 16-wire cathode and require many times the cathode heating power. Of course, if the length of the cathode is doubled in any case, the perveance is doubled; but otherwise, when wire cathodes are used, the perveance does not necessarily increase linearly as the number of cathode wires is increased. This is the reason for the α in equations 1 and 3. It is also the reason why wire cathodes are used so extensively; that is, in order to obtain the highest perveance per watt of cathode power. The total cathode current density is limited by the required life of the cathode. Since emission density increases and cathode life decreases as an exponential function of cathode temperature, and since pulsed radar requires high peak powers, a compromise must be made between tube size and cathode life.

2. High Voltage Stability

The equations given above permit calculation of tube data with an error of 10% or less. However, in order to complete the design of a tube, it is necessary to consider one factor; i.e., will the peak voltage between electrodes cause excessive field emission and internal tube breakdown or flash arcing? Fortunately, closer grid-to-cathode spacings require less positive grid drive voltage, and it happens that there is no problem in designing tubes which do not initiate arcs between grid and cathode. The control-grid to plate, or screen-grid to plate spacing is another matter entirely. Here a compromise must be made between higher tube efficiency and voltage stability. From equation (5) it is obvious that, d, the outer grid to anode spacing, should be made as small as possible to have the lowest possible e_p or plate voltage drop during the pulse. However, this spacing, d, must be large enough so that the vacuum insulation between outer grid and plate does not fail at the maximum plate to grid potential for which the tube is rated. In order to design a tube it is necessary to know what the maximum electric field gradient at the grid can be without danger of excessive flash arcing. Kirkpatrick[6] has given a summary of the empirical data on breakdown between plane parallel electrodes. His data is given by curve A in Figure 3 showing voltage against spacing. Since electron tubes using cylindrical structures with wire grids have higher voltage gradients at the grid wires than do parallel plane sheet metal electrodes, the maximum voltage for practical tubes is lower. Since low-amplification-factor triodes have fewer wires and usually finer wires, the maximum plate voltage hold-off capabilities depend somewhat on the amplification factor. For this reason a shaded area, B, on Figure 3 indicates roughly the values of plate hold-off voltage for tubes with thoriated-

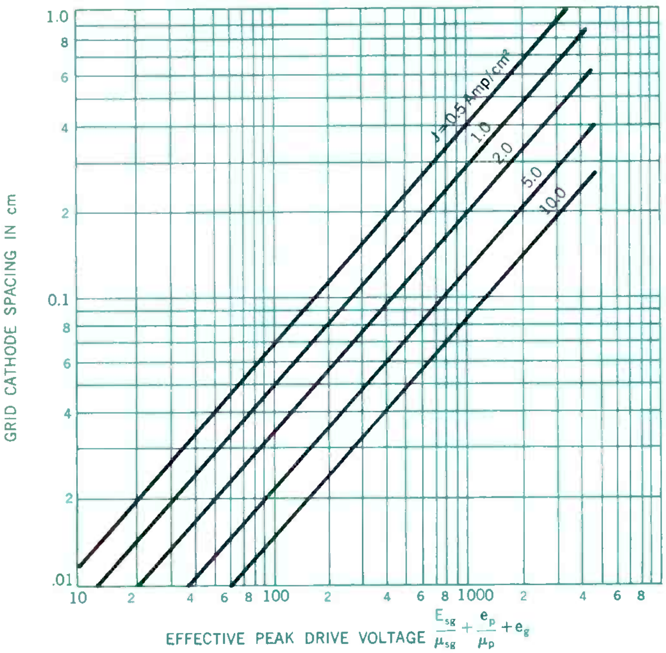


Figure 2 — Effect of grid to cathode spacing on required drive voltage for various cathode current densities, J.

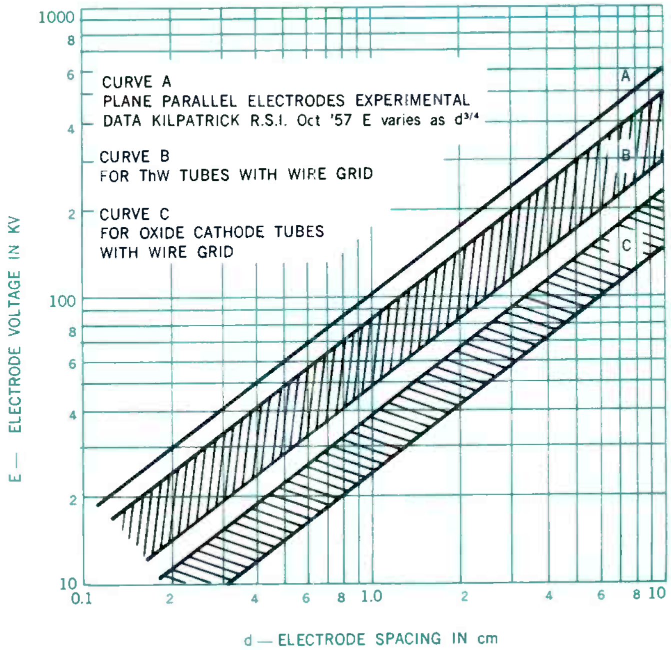


Figure 3 — Anode Voltage Rating versus Outer Grid to Anode Spacing.

tungsten cathodes and cylindrical structure grids. Another area, C, at still lower voltages is shown for tubes using oxide cathodes. In the latter case it appears that the products of decomposition of the oxide cathode cause the grid to become contaminated with a surface layer which has either a lower work function or has a greater roughness. It is well known that the maximum voltage gradient which any surface can support without sparking depends on the surface conditions. The best possible polishing will certainly improve the situation. In large tubes with many feet of wire, however, it is not feasible to perform optical polishing of grids. Furthermore, the result of a single tube arc could destroy the effect of such polishing.

One can read from the upper curve of Figure 3 the maximum permissible voltage gradients, E, for the parallel plane sheet metal case, since here the gradient is simply the voltage divided by spacing. It should be noted that this curve follows the equation $E \propto d^{3/4}$ and therefore at the higher voltages the maximum permissible gradient is lower. The lower curves are based on the calculated voltage gradients at the wire grids and on observations obtained from a series of tubes. Of course one has to know the actual geometry of a given tube in order to calculate the voltage gradients.

3. Cathodes for Pulse Modulator Tubes

At the present time only oxide and thoriated-tungsten cathodes are generally used. Extensive experience with thoriated-tungsten cathodes, see Figure 1, in transmitting tubes has demonstrated that the life of such cathodes is predictable.[7] The usual large transmitting tube cathode delivers 30 milliamperes per watt of cathode power with a safety factor of two in order to permit satisfactory operation at the rated —5% on filament voltage. Under such conditions cathode life is greater than 10,000 hours. If the filament voltage is closely regulated, say ± 1%, cathode currents up to 60 milliamperes per cathode watt can be obtained without much sacrifice in life. Higher emission can be had only at a corresponding reduced life. Peak cathode emission density of 3 amperes per square centimeter is compatible with the 10,000 life figure given above. With round wires it is seldom feasible to pull uniform emission density all around the circumference of the wire and therefore the average emission density will be less. Emission from thoriated-tungsten cathodes is independent of pulse width. The usual limiting factor on pulse width in such a tube is the rise in grid temperature. Excessive grid temperature causes the grid to emit; that is, to become a cathode with consequent loss of control by the grid.

Oxide cathodes have been used in switch tubes with maximum plate voltages of 75 kilovolts. (See Figure 4.) The advantages of the oxide cathode tubes are: smaller size, lower heater power for a given emission level, and better mechanical strength. Such tubes can be made so that they can be mounted in any position, and at least one design, the 7333, at the 300 peak kilowatt level has operated at rated power output on the vibration table from 30 to 2000 cycles per second at 10 g. On the other hand, it is not yet possible to predict the life of an oxide cathode over widely varying conditions. The 6544 operates at 2 amperes per square centimeter and 200 milliamperes per cathode watt. This tube has been evaluated on life test with pulse lengths of a few microseconds and a duty of about .0015. Under such operating conditions in laboratory life test equipment using a resistance load, average life is in excess of 3000 hours. In

Figure 4 — ML-6544 oxide cathode structure with grids and anode.

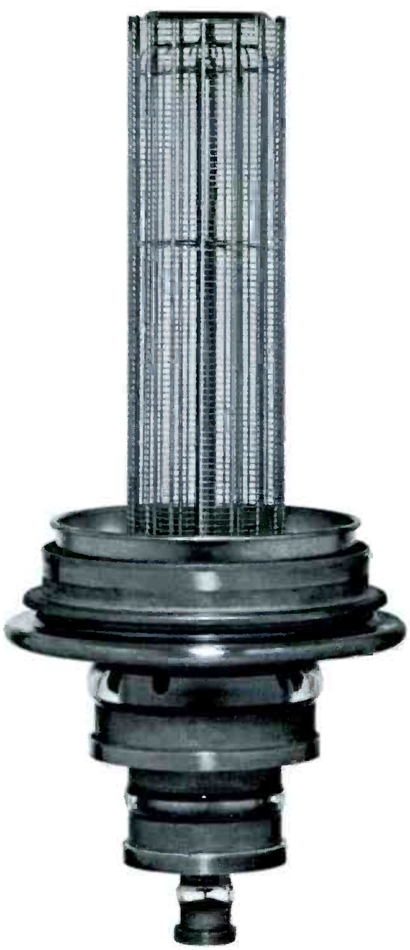


Figure 5 — A typical helical grid structure mounted over thoriated-tungsten cathode, ML-5682.

the case of the 6544 at .0015 duty, the grid dissipation is only about one-tenth the maximum capability of the grid. It appears feasible in this tube to extend pulse lengths to several hundred microseconds and/or increase the duty.

In oxide cathodes, life is dependent on cathode temperature, emission density, type of cathode nickel and residual gases. Improvements in cathode base nickels, tube processing and quality control can be expected to produce higher peak and average emission levels for very long life. Such development work requires continuous life test evaluation. Similarly it is necessary to monitor tube life on production sampling at the maximum ratings. Present life capability is purely empirical. For the above reasons commercial tube data sheets specify values of peak emission, pulse width and duty cycle for which the tube is monitored. Whereas any individual tube may operate satisfactorily under conditions considerably beyond the published limits, one cannot be sure that any tube bearing the same type number will do likewise.

4. Grids for Pulse Modulator Tubes

Grids usually consist of meshes or helices wound on vertical stays. (See Figure 5). The grids are almost invariably of tungsten or molybdenum, although they may be coated with platinum or gold or other materials to make them operate at higher dissipation levels without becoming emitters themselves. The screening fraction of the grid, i.e., the ratio of the area obstructed by the grid wires to the total area of the grid structure varies from 5 to 25%. The grid wires are usually made as small in diameter as is mechanically feasible. They must also have enough thermal capacity so that a localized arc will not result in the melting of a short section of wire. The spacing between grid wires is

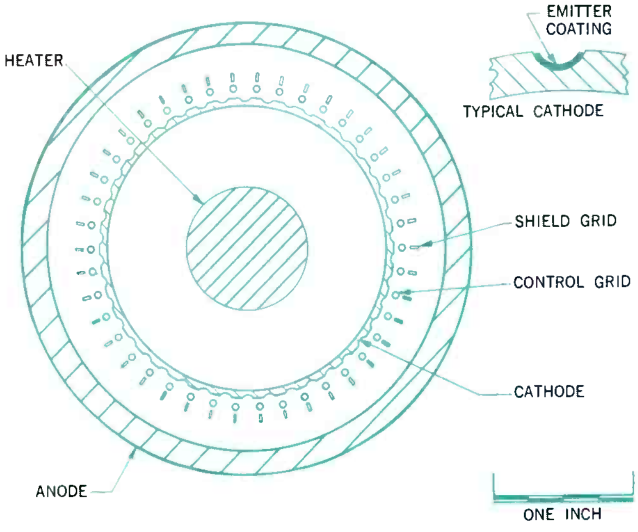


Figure 6 — Right section through active electrode area of ML-6544 showing beamed grid and cathode structures.

usually about equal to the grid cathode spacing in order that the grid have uniform control of the entire cathode emitting area[8]. This latter restriction means the use of a closer knit mesh and finer wires as the grid cathode spacing is reduced.

Typical "end-of-load-line" values for plate and grid currents depend on the screening fraction of the grid. Very roughly the percentage of the cathode current which goes to the grid will be about 1.5 times the screening fraction in per cent. Consider two tubes using the same cathode structure and interelectrode spacings but with different grid screening fractions. The low amplification factor tube, about 20, will have a screening fraction of about 10% and the grid current will be about 15% of the cathode current. The tube with a high amplification factor will have about 25% of the cathode current going to the grid. Conversely, the low amplification factor tube will require more negative bias to prevent plate current flow during the interpulse period. As far as grid driving power is concerned, it is very nearly the same for either tube.

Some triode tubes have been made with very low amplification factors, about 5. These tubes can pass reasonably high plate currents without driving the grid positive; see equation (6). Although a large negative bias is required in the inter-pulse period, the driving power can be quite low. Unfortunately, this cannot easily be done with high voltage tubes, since the large grid-anode spacing required to provide adequate high voltage insulation raises the amplification factor too much, even with low screening fractions on the grid.

The maximum permissible grid temperature determines the maximum dissipation rating of the grid. It also determines the maximum width of a single pulse. Neglecting radiation loss from the grid, and assuming the entire volume of the wire is heated instantaneously, the maximum rise in temperature of a grid during a pulse would be given by,

$$\Delta T = \frac{0.24\,P}{(s)\ (m)}\,\tau \qquad (7)$$

where ΔT = temperature rise in °C
P = watts dissipated in the grid
τ = pulse length in seconds
s = specific heat of the grid material
m = mass of the grid in grams

Since grids can operate to temperatures as high as 1400°C, radiation losses are significant and make possible higher grid dissipation ratings than the above formula indicates. This subject of grid dissipation will be discussed further in a later section. For the usual transmitting type of tube, the maximum length of a single pulse at rated power output is usually limited to 10 milliseconds or less.

Since grid current is undesirable and grid dissipation may be a limiting factor in tube operation, tubes have been made with grids so positioned as to substantially reduce grid current. (See Figure 6.) These tubes utilize a type of gun structure with relatively long strip cathodes set in a focusing groove. The grids consist of relatively large diameter rods parallel to the emitting cathode strips. These grid wires are spaced on either side of, and somewhat forward to, the cathode emitting area such that they are not in the path of the main electron beam[9, 10]. Such tubes are capable of extremely long pulses as far as the grid is concerned. Since such grids intercept much less space current, the driving power for such a tube is lower than the type of triode discussed earlier, although the amplification factor may be from 50 to 500. The 6544 tube has a μ of 90, hold-off capability in excess of 20 kilovolts, and the grid current is less than 10% of the cathode current.

In the case of conventional tetrodes, control-grid dissipation is not a problem, since intercepted grid current is kept low and so is the positive grid drive voltage. In this case the screen-grid dissipation is the limiting factor and is subject to all the restrictions of the control grid of a triode.

5. Anodes for Switch Tubes

Anodes for radiation cooled tubes are usually of molybdenum sprayed with a zirconium getter powder. The use of copper for forced-air or liquid cooled tubes is general. Although radiation cooled tubes have been built for 3 kilowatts of dissipation, they are only usable if the associated circuit components are several feet away. In general, any rating over 100 watts is objectionable due to space problems. For copper anode tubes, anode dissipation presents no serious problem since liquid or forced-air cooling can be used.

Equation 7 with appropriate values is applicable in evaluating anode dissipation density. Of course one has to consider conduction cooling, anode wall thickness and temperature gradient through the copper[11, 12].

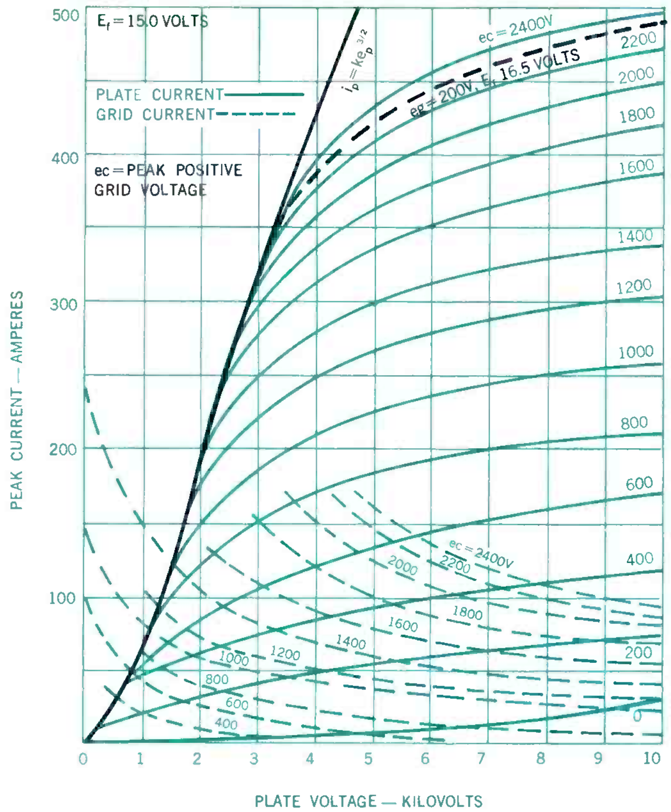


Figure 7 — Constant Grid Voltage Characteristic Curves of ML-7560 showing End-of-Load Line Point and Diode Curve $i_p = ke_p{}^{3/2}$.

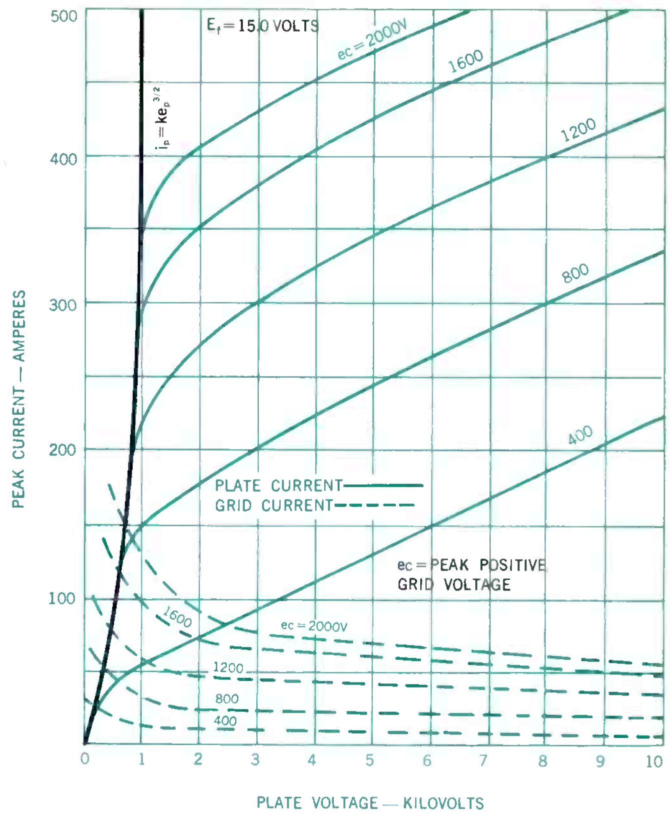


Figure 8 — Constant Grid Voltage Characteristic Curves of ML-8547, showing effect of reduced grid anode spacing on the Diode Curve $i_p = ke_p{}^{3/2}$.

6. Interelectrode Capacitances and Amplification Factor

The grid (or screen-grid) to anode spacing and the anode surface area determine the grid-anode (or output) capacitance. It has been shown that the outer grid to anode spacing is determined by voltage breakdown considerations. Furthermore, it has been shown that the anode area is determined by the minimum acceptable tube efficiency. In other words, the grid to plate capacitance of a triode or the output capacitance of a tetrode is not an arbitrary design parameter. It is fixed by other considerations except insofar as the capacitance of the electrode support structures and tube envelope can be kept to a minimum. Similarly, the grid cathode capacitance of a triode or the input capacitance of a tetrode is determined by the choice of the quantity, S, the equation (1). If it is required to minimize the peak positive value of e_g in equation (1) for the maximum value of $i_k/\alpha A$, the only independent variable that can be selected is S, the effective grid-cathode spacing. It should be recalled that $i_k/\alpha A$ has a limited maximum value based on the required cathode life. In order to decrease the maximum value of e_g (to reduce the grid drive voltage and power), it is necessary to increase the input capacitance. Although the input tube capacitance increases as the grid is moved closer to the cathode, the total energy stored in this capacitance, in order to raise the grid potential to the desired value, decreases approximately linearly with the spacing. Since both the driving power and the capacitance charging energy decrease with decreasing grid-cathode spacing, it is obviously desirable to make this spacing as small as possible, even though it causes a loss in plate current density (equation 5). Practical grid-cathode spacings are determined by how small a grid wire can be used at how close a spacing and still maintain a uniform grid-cathode spacing throughout life.

The only capacitance in a triode which can be varied appreciably by the tube designer is the plate to cathode capacitance. For a fixed grid-anode spacing this capacitance determines the amplification factor of the tube. As shown in section 4, the net result is that either type of tube requires about the same driving power. As regards to capacitance charging currents, again there is a balance. The lower amplification factor tube may have a little lower grid-cathode capacitance, but it requires a higher total grid voltage swing. In general, the choice of amplification factor will depend on other circuit considerations such as driver tubes, use of pulse transformers, etc. For tubes designed to operate at low plate voltage, the outer-grid to anode spacing can be made smaller and, by equation (5), the current density in the grid-anode space can be higher. (See ML-7560 data vs. ML-8547, Figures 7 and 8). Even so, the grid-anode capacitance will increase due to this closer spacing, and the $\mu\rho$ will decrease unless the screening fraction of the grid is also increased at the same time.

The input capacitance of a tetrode will be higher than that of a triode of the same cathode emitting area, since the capacity from the control-grid to the screen-grid is in parallel with the control-grid to cathode capacitance. As regards the capacity charging currents and drive power, both will be reduced, since the total grid voltage drive from cut-off to maximum positive drive is substantially reduced over triodes. Where fast rising pulses are encountered, the tetrode seems attractive since its plate to control grid capacitance is much lower than for triodes. In order to consider the effective total input capacitance, it is necessary to write an equation for the "Miller Effect" for triodes or tetrodes:

$$C \text{ in eff} = C_{in} + C_{gp}\left(\frac{e_p}{e_g} + 1\right). \quad (8)$$

where = C in eff = effective total input capacitance
C_{gp} = plate to control grid capacitance
C_{in} = measured tube input cap. from grid to cathode (and screen-grid), anode grounded
e_g = pulse input grid voltage
e_p = pulse output voltage

Since the ratio of e_p to e_g for a tetrode is increased by about the same amount as the capacitance, C_{gp}, is decreased over that for a triode, effective total input capacitance of a tetrode is about double that of a triode. Of course the necessary grid swing is smaller for the tetrode.

Characteristic Curves and Principal Data for Some High Vacuum Pulse Modulator Tubes

The preceding paragraphs discussed briefly the design consideration for Vacuum Tubes. From these sections one can calculate all the pertinent data required for the circuit engineer. It is conventional to present absolute maximum ratings on such items as plate voltage, grid voltage, grid dissipation, plate dissipation, etc. Similarly interelectrode capacitances, filament voltage and current are given. Since it is not feasible to give an analytical relation between electrode voltages and currents, a graphical presentation is made. Usually these "Characteristic Curves" are given for 1, plate current and grid current vs. plate voltage with constant grid voltage curves as a parameter; or 2, grid voltage vs. plate voltage with constant plate and grid currents as parameters. The data for these curves are taken with microsecond pulses at a low repetition rate. The curves are referred to as static characteristics, since they give instantaneous values of currents for corresponding values of electrode voltages. It is possible to determine the dynamic characteristics for any load conditions from these static characteristics.

With vacuum tubes it is necessary that the plate current be negligibly small during the interpulse period. For this reason, a curve of plate voltage versus grid bias for cutoff conditions or a value of μ for cutoff is given (Figure 9). Since the interpulse period may be very long compared with the pulse duration, a plate current of a few milliamperes can cause an appreciable anode dissipation. Pulse modulators should have a sharp cutoff characteristic because the required negative bias voltage must be added to the positive grid drive in order to determine the total grid swing. Also the range of cutoff bias voltage for different tubes of the same type should be small, since the circuit designer must accommodate the poorest tube. The cutoff bias will vary with the plate voltage of a triode and with both the plate and screen-voltage of a tetrode. The pulser must be designed to provide a bias voltage large enough to be effective for the highest plate and screen-grid voltages that may occur in operation of the pulser, particularly when load inductance may cause the instantaneous plate voltage to go considerably more positive than the dc voltage. It is usually not practical to specify that the tube shall be biased to zero plate current, particularly in high voltage tubes. A compromise must be made between added grid drive power and plate dissipation. If there are oscillations on the grid drive following the pulse, it will be necessary to bias sufficiently such that plate current does not flow at the positive going peaks of such oscillations.

High voltage tubes may have some field emission from the grid. In such cases it is not possible to reduce this current by the use of additional bias since this current comes from the grid facing the anode. Tube specifications should give a maximum value for such currents. It should also be noted that plate current flowing at high plate voltages continuously in the interpulse period will give rise to appreciable x-rays. It is necessary to shield high voltage equipment for personnel protection.

1. Characteristic Curves of Triodes.

In order to illustrate the typical regions of the characteristic curves of triodes, the ML-7560 tube will be discussed. This tube uses a thoriated-tungsten wire cathode (Figure 1). Constant positive grid drive voltage curves are given in Figure 7, showing plate current and grid current as a function of plate voltage. It is to be noted that the area to the left of the line marked $i_p = K e_p^{3/2}$ defines a region where it is not possible to get any current to the plate. From the grid current curves it is obvious what is happening. It is seen that the grid current rises as the plate current decreases while the sum of the two currents is nearly constant. The reason for this situation is that a virtual cathode is established in the grid-anode space, i.e., the effective potential somewhere between the grid and the anode has dropped to zero (cathode potential) or below. When this happens, the current arriving at the plate is determined by the plate potential and the position of the virtual cathode as follows:

$$i_p = 2.33 \times 10^{-6} A e_p^{3/2} / s^2 \quad (9)$$

where i_p = current to anode in ma.
A = area of virtual cathode in cm^2

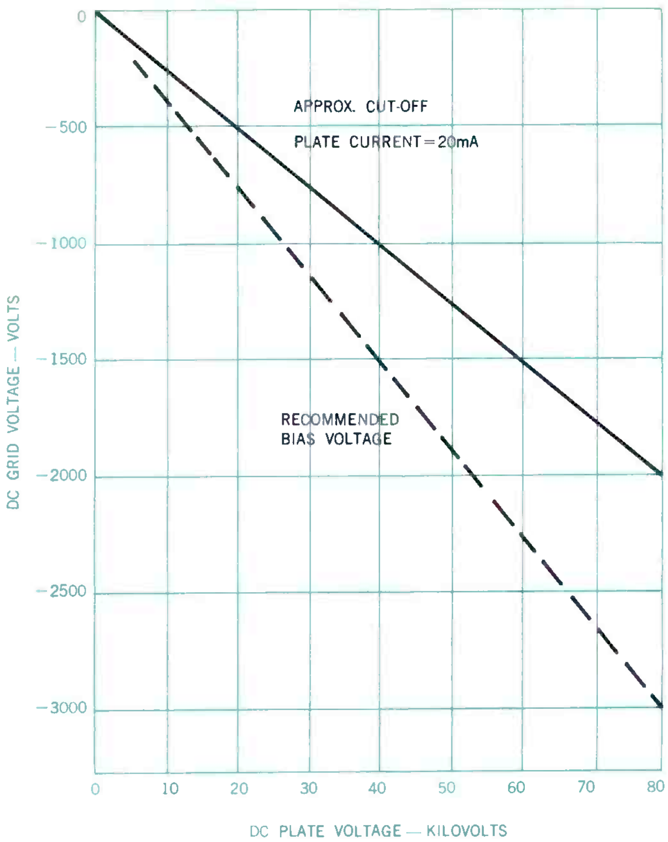


Figure 9 — Grid Bias versus Plate Voltage for cut-off in inter-pulse interval — ML-7560.

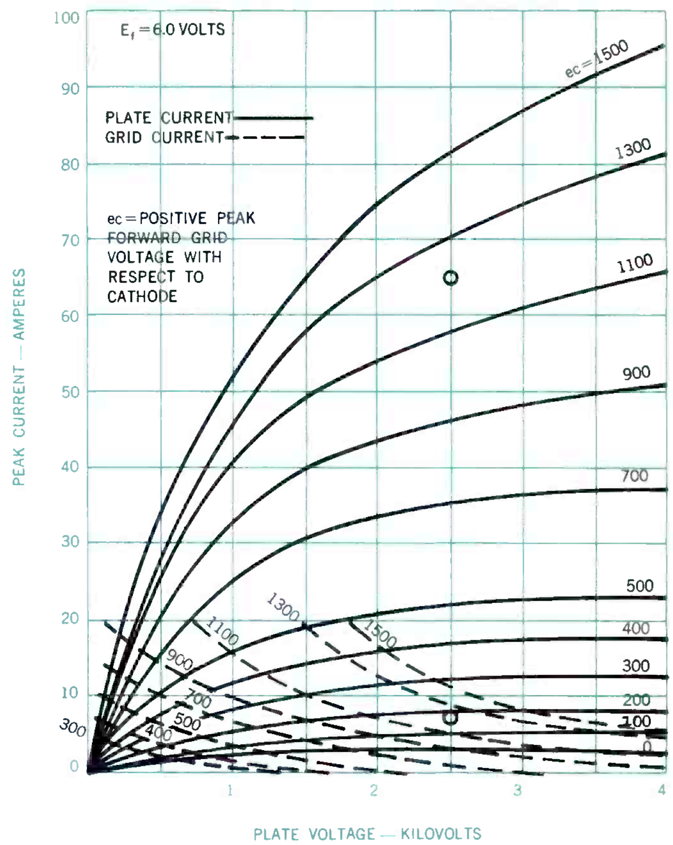


Figure 10 — Constant Grid Voltage Characteristic Curves of ML-6544.

e_p = plate voltage in volts
s = spacing from virtual cathode to anode in cm.

The area of the virtual cathode in this cylindrical electrode tube is the area of an hypothetical cylinder approximately half-way between the grid and the anode, and of length equal to the cathode length. When such a virtual cathode is formed, electrons passing through the grid are brought to rest and those that do not go to the anode (equation 9) are returned to the grid. This result is predictable from equation 5. This tube was purposely picked to illustrate equation 5, since the grid-anode spacing is large enough to hold off 60 kilovolts and the effect of the virtual cathode is more obvious than in closer spaced lower voltage tubes. Comparison of these data with those for a similar tube with a much smaller grid anode spacing and a lower value of maximum plate voltage (Figure 8) emphasizes the increase in "tube drop" with increased spacing. The overall plate efficiency does not change much since the dc plate voltage is correspondingly higher for tubes with greater spacings. The actual current density arriving at the anode at the end of the load line point, P, on Figure 7 is about 0.5 amperes per square centimeter of *anode* surface. Assuming that more cathode emission was available, it would be necessary to raise both grid and anode potentials in order to increase the total anode current. Such a procedure would mean that the tube drop would have to increase and the efficiency would decrease, since the maximum dc plate voltage is fixed. In other words, the use of more cathode wires or even a solid cylindrical sheet cathode without increasing either cathode length or diameter, cannot substantially increase anode current without materially lowering the tube efficiency. A properly designed tube balances total available cathode emission against that current which can cross the grid-anode space at reasonable plate efficiency, i.e., about 90%.

Another feature of the curves of Figure 7 is the gradual upward slope of the plate current curves to the right of the space-charge knee, and the corresponding downward slope of the grid current lines. Three factors contribute to these slopes. The most prominent effect is due to the term $e_p/\mu\rho$ in equation 6. It is seen from this equation that even if e_g is held constant, the total cathode current must increase, as the anode voltage increases. The higher the amplification factor of the tube, the flatter is the plate current versus plate voltage curve at fixed grid drive. A second factor is that the ratio of i_p to i_g increases as the ratio of e_p to e_g increases (see equation 4). This means that the plate current will rise while the grid current decreases. A third factor is secondary grid emission which becomes more pronounced at higher plate voltage. At low grid drives, that is a few hundred volts positive, the ratio of secondary electrons to primary electrons may exceed one. If the plate voltage is high enough, all these secondary electrons go to the plate and a negative grid current results (See Figure 13).

It should also be noted that the spacing between plate or grid current lines for a constant increment of grid drive voltage is fairly constant except at the higher grid drives. When plate current does not increase as could reasonably be expected by an appropriate increase in grid voltage, it is because one is running out of cathode emission. That part of the cathode closest to the grid becomes saturated in emission, and increased grid drive results only in reaching around to the back of the cathode wire where the field is not yet strong enough to take all the available emission. Raising the filament voltage will now give increased emission. Note the line marked Ef + 10% at 2000 volts in Figure 7. Such an increase in filament voltage reduces cathode life appreciably.

2. Characteristic Curves of Shielded Grid Triodes

Another type of triode switch tube is the shielded grid type with a beamed cathode structure. This type of triode has a high amplification factor and yet takes very little grid current. Examples of this type are the 6544, 7003, 7845. For discussion here we consider the 6544 (See Figures 4 and 6).

This design uses about 40 straight cathode strips .060″ wide, spaced with about .080″ separation between adjacent parallel strips. These cathode strips are arranged to form a cylinder of about 2″ in diameter. Located outwardly and slightly in front of the gaps between these cathode strips is a squirrel cage grid of .070″ molybdenum wire. On a somewhat larger bolt circle is a molybdenum shield grid also using .070″ molybdenum wires. This shield grid is tied to one end of the cylindrical cathode by a metal disc. The control grid wires feed through this disc to the external grid electrode terminal. Surrounding the shield grid is a copper cylindrical anode with about a 0.2″ radial spacing between it and the shield grid.

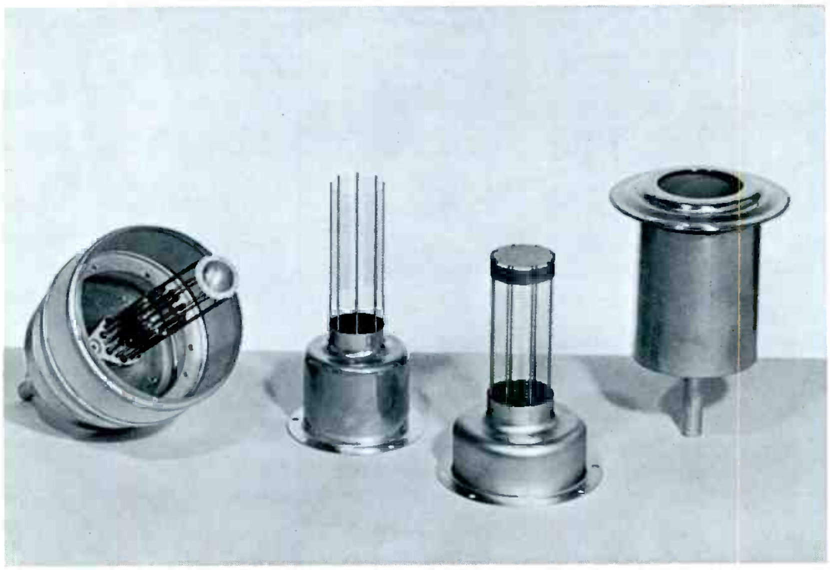
The principal arguments in favor of this design are: (1) by proper cathode shaping one can keep control grid current low, (2) shield grid current will be zero since this grid is at cathode potential, (3) any arc to the shield grid will not transfer to the cathode since lead impedance between shield grid and cathode is zero, (4) the shield grid can withstand heavy arcing if necessary without distortion, (5) neither grid will be required to stand appreciable dissipation, i.e., there will be no question of primary emission troubles even with abnormal use, (6) the structure is rugged, (7) no screen grid power supply is required, (8) the amplification factor is high and only a modest negative control grid voltage is required for cut-off.

Although the grid current is low in this tube, it is seen that at low plate voltage the grid current rises rapidly. The drop in plate current equals the rise in grid current; i.e., a virtual cathode is forming between shield grid and plate. The slope of the plate current versus plate voltage curve at constant grid drive is determined by the amplification factor of the tube, with μ about 60, the curves are fairly flat from 3 to 20 KV (See Figure 10).

3. Characteristic Curves of Tetrodes

A well known pulse tetrode is the 7007. Since this tube has been widely used and it exhibits typical tetrode characteristics, it will serve as an illustrative example of this class of tubes. Figure 11 shows the tube, and Figure 12 shows the

Figure 11 — View of cathode, grids and plate of the ML-7007 tetrode.



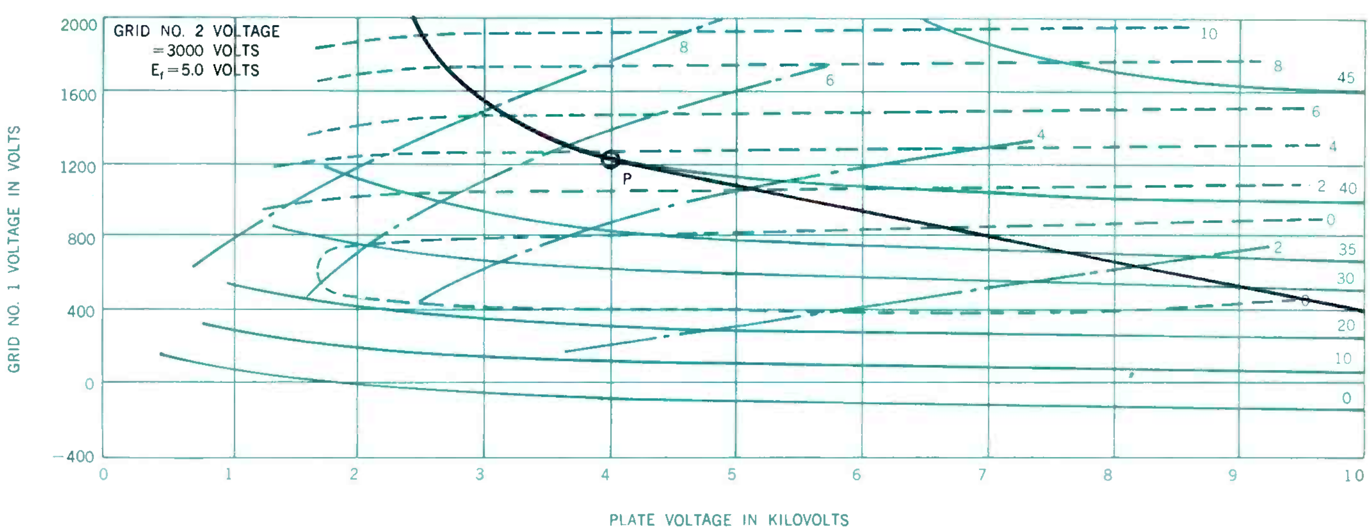
grid drive voltage versus plate voltage for constant plate and control grid currents at a screen grid voltage of 3000 volts. Since the screen-grid shields the cathode from the high plate potential, the cut-off bias is determined primarily by the screen grid voltage and its amplification factor of 10. See equation 1. The total grid swing required to obtain the rated cathode emission is less than for a triode, and little control grid current is drawn. The grid current is not appreciably affected by plate voltage variations. However, when the plate voltage is decreased far enough, a virtual cathode forms between the screen grid and anode with the resultant decrease in anode current and corresponding increase in screen-grid current, just as in the case of the triode for the control grid to anode region. The plate and screen grid current curves clearly show virtual cathode formation. For plate voltages higher than twice E_{sg}, the slope of the plate current curves reflect the high plate amplification factor of this tube. The spacing between the screen-grid and anode in this tube is about the same as that of the 6696 and considerably less than that of the 7560 triode. The 7007 tube is rated to hold off only 25 kilovolts compared to 45 kilovolts for the 6696. This relatively low voltage rating on the 7007 is due to the length of the ceramic envelope and not to internal electrode spacings. Some further problems on voltage stability will be discussed later.

Use of the Characteristic Curves to Determine Dynamic Operating Conditions

A "load line" is selected on a set of grid voltage versus plate voltage static characteristics in much the same manner as is done with Class C operation of CW amplifiers or oscillators. [13] For a first approximation, it is assumed that the load impedance is to be pure resistance. In this case the load line on the above characteristic curve will be a straight line. In order to select a tube it is necessary to first specify the required pulse voltage and pulse current for the load. If a pulse transformer is used, then the peak pulse power can be used to select a tube as the transformer will permit stepping up or down the voltage delivered from the tube (See Appendix I). If it is desired to work from the pulse modulator tube directly into the load, then a modulator tube must be selected such that the maximum dc plate voltage is approximately 10% greater than the required pulse voltage to be delivered to the load. It is also necessary that the tube selected be capable of delivering the required output pulse current. (Of course two or more tubes may easily be used in parallel). Having found a tube or tubes capable of the required output voltage and current, the next step is to determine the cut-off bias required during the interpulse interval when the modulator tube is supposed to be passing no current, i.e., the switch is open. Usually (Figure 9) a curve will be included with the tube data showing recommended bias voltage for various plate voltages. If such a curve is not included, a good rule is to use approximately 30% more bias voltage than for Class B amplifier operation. This additional bias is required to assure that plate current is negligibly small in the interpulse interval and to make certain that any oscillatory conditions at the end of the grid pulse do not give rise to appreciable plate current pulses following the desired output plate current pulse. The cut-off end of the load line has now been determined. See Figure 13. Next one picks a point of positive grid drive which from the grid voltage vs. plate voltage characteristic curves gives the required plate current to the load. This is the switch on condition. Selecting this point involves a compromise on grid driving power and plate efficiency. If such a point is picked at very low plate voltage, the output circuit will attain the highest efficiency, but the grid drive power may well be excessive. The result may be to overload the control grid or screen grid. Hence, if such a point were picked, the grid dissipations should be checked to see that these maximum ratings are not exceeded.

Figure 12 — Constant Current Characteristic Curves for ML-7007, operating point "P."

PLATE CURRENT, AMP
GRID NO. 2 CURRENT, AMP
GRID NO. 1 CURRENT, AMP



In the case of triodes, the operating point will usually be where the peak grid current is from 10 to 30% of the peak plate current. In tetrodes, the operating point should be picked such that the screen grid current is not excessive as regards the screen grid dissipation limit. (See Figure 12) When these two points have been spotted on the characteristic curves, a load line can be drawn as a straight line terminating on these two points. This line shows what the instantaneous plate current, grid current and plate voltage will be for any specified grid voltage wave form (Figure 13).

In equipment operation it is necessary to consider effects of variation of dc plate voltage, dc screen voltage and the effect of variations of amplitude of the grid driving pulse. (For a more detailed analysis see Ref. 14.) The effect of variation in grid voltage on the output pulse of the pulser may be illustrated by drawing the load line on the plate-current plate-voltage characteristic curves for fixed grid drives. An examination of the characteristics of triodes, shielded grid triodes and tetrodes, for example, Figures 7 and 10, show that the form of these curves follow a general pattern. For an approximate solution to the problem of regulation, i.e., variation of grid pulse amplitude or flatness of the top of the driving pulse, a simplified set of curves may be used as shown in Figures 14, a and b, where A, B, C . . . represent different constant grid drive voltages. These curves can be expressed mathematically by the equation:

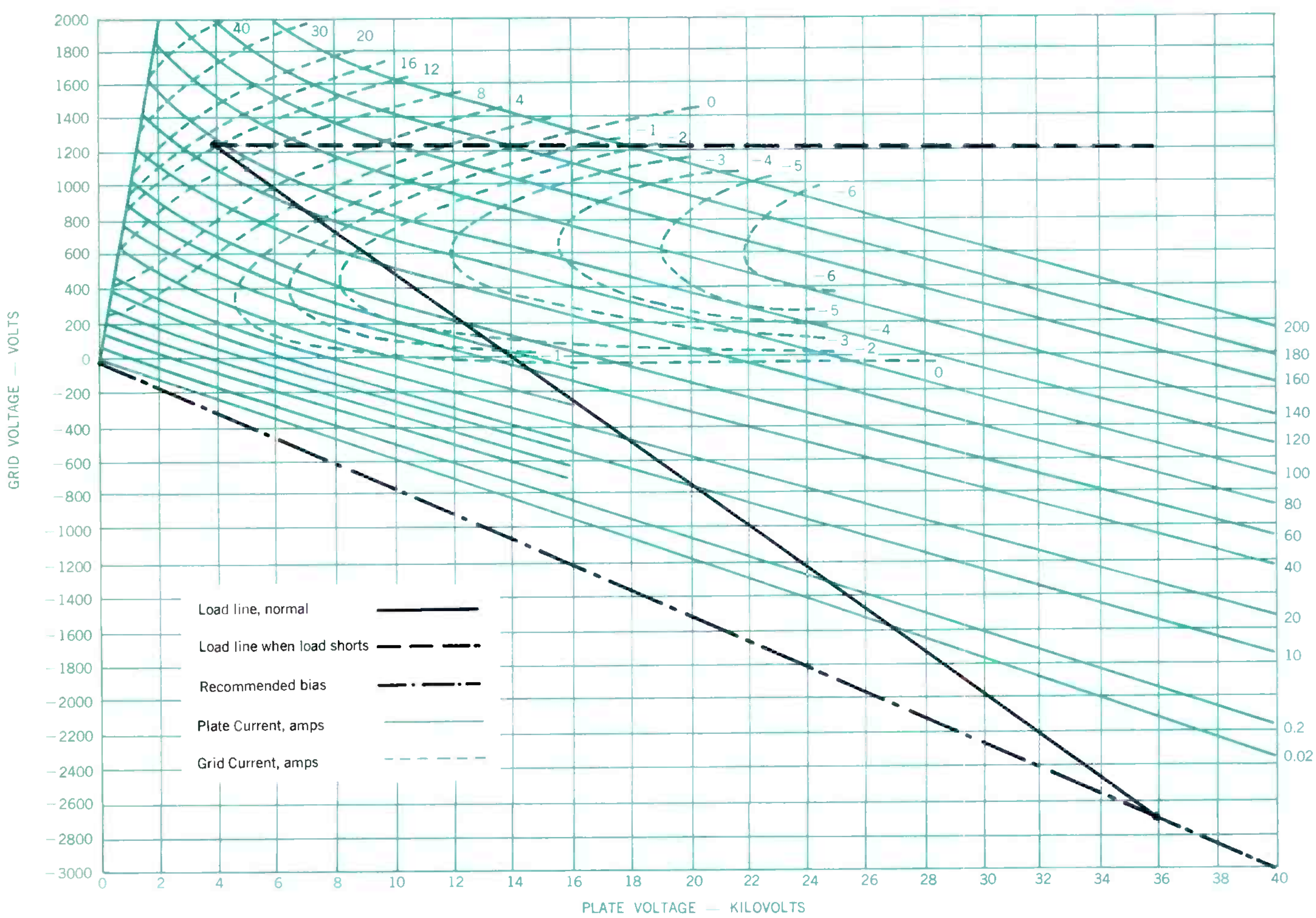
$$i_p = c\,(e_g + E_{sg}/\mu_{sg} + e_p/\mu_p) \qquad (10a)$$

with the following restrictions:

$i_p < \sigma e_p$
$i_p > 0$
$e_p > 0$
σ = conductivity of diode line
c = constant obtained from end of load line on characteristic curves.

Two load lines are drawn on the curves shown in Figure 14a. Line E_{bb} — E_d — Opl corresponds to a low resistance load in series with a bias voltage, E_S, to simulate magnetron operation, where $E_{bb} - E_d = E_S$. The straight line connecting E_{bb} and Opl corresponds to a fixed resistance load of the same magnitude as the static resistance of the biased diode for the operating point, Opl. From this diagram it is evident that a change in the grid driving voltage corresponding to the curves A, B, C has no effect on the operating point for the switch tube. For actual tube characteristics the various

Figure 13 — ML-6696 Constant Current Characteristic Curves showing Reverse Grid Current Area, recommended dc bias, typical Load Line and Load Line when load shorts.



grid drive lines represented by A, B, C, etc., do not all follow down the diode line given by $i_p = \sigma e_p$ and curves A, B, C . . . are more or less rounded off as they approach the limit line on minimum plate current. Nevertheless, these curves can be used to determine with fair accuracy the effects of variations in grid drive, screen grid voltage and plate voltage, provided the changes are small.

If adequate positive grid voltage is provided to keep the operating point for the tube (Op1 Figure 14a) somewhat below the knee of the characteristic curve, irregularities in the top of the grid driving pulse are not observed on the output pulse. This consideration is of considerable importance to the design of the driver circuit. Since such operation results in high grid currents in a triode and high screen-grid currents in a tetrode, care must be taken to assure that excessive grid dissipation does not result. Furthermore, such operation requires a well regulated dc plate voltage supply for the pulser tube.

If the operating point Op2 is on the curve C of Figure 14b, and the grid voltage changes over the range from B to D, a different situation obtains. In this case both the load voltage and the load current are affected by variations in grid drive voltage. For the low-resistance biased diode load, a change in the e_g from C to D results in a load voltage change of ΔV_1 and a change in load current of Δi_1. Similarly, for the higher resistance load without a biasing voltage, the corresponding changes are ΔV_2 and Δi_2. Because of the upward slope of the constant grid drive curves above the knee, the change in current is greater for the low-resistance biased diode load and the change in voltage less. When a switch tube is operated in this manner, irregularities in the grid-voltage pulse are transferred to the load pulse.

Of course if the load has reactive components, See Figure 16, the load line will depend on the instantaneous impedance and will form a loop of some sort. Since the curves of Figures 14 a and b include the effect of both screen-grid and control-grid variations, it should be pointed out that the combination of variations of both screen-grid voltage and pulse grid drive must be considered in regard to the critical drive line C, Figure 14a. Because of the flow of pulse current to the screen-grid and the plate to screen-grid capacitance, it is necessary to provide a large bypass capacitor between the screen-grid terminal and the cathode. If fast rising pulses are used, the self-inductance and the load inductance of this capacitor must be made small enough to give a low impedance at the maximum useful frequency component of the pulse. The use of grid drive saturation to give flat top pulses is usually confined to low or medium power stages. It tends toward excessive screen-grid dissipation in tetrodes, and excessive driver output current and grid dissipation in triodes. In shield-grid triode devices, the use of grid drive saturation is usually satisfactory even in high power tubes, because the grid is capable of handling high dissipation compared to that of its normal pulse amplifier rating.

If the operating point is taken above the knee of the curves, Op2 on Figure 14b, the effects of variation in grid drive voltage, screen-grid and/or plate voltage can be found by rearranging equation 10a and differentiating;

$$i_p = \frac{1}{\frac{i}{c} + \frac{rl}{\mu_p}} \left(e_g + \frac{E_{sg}}{\mu_{sg}} + \frac{E_{bb} - E_s}{\mu_p} \right) \qquad (10b)$$

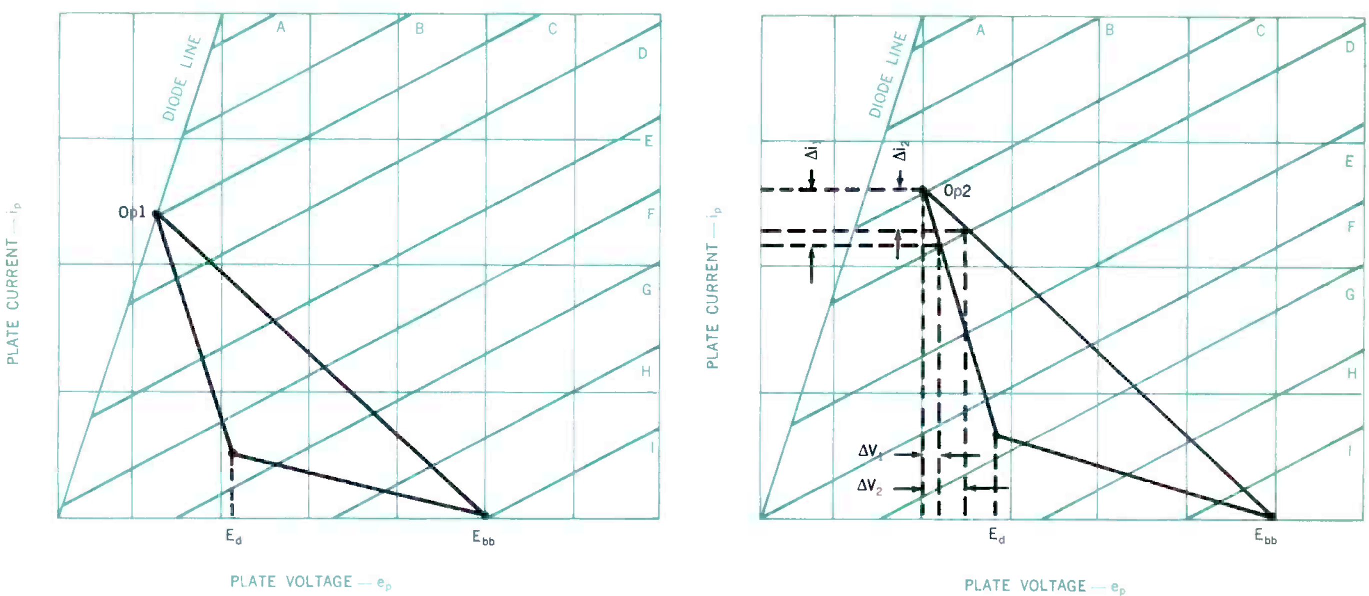


Figure 14 — Simplified Constant Grid Voltage Characteristics for any vacuum tube:
a) load line to operating point below knee of plate current curve
b) load line to operating point above the knee of plate current curve.

where rl is the dynamic impedance at the Op2 point, Figure 14b, E_S is the starting voltage of a magnetron or the dc value of a biased diode load.

$$\frac{\partial i_p}{\partial e_g} = \frac{1}{\frac{1}{c} + \frac{rl}{\mu_p}} \quad (11a)$$

$$\frac{\partial i_p}{\partial E_{sg}} = \frac{1}{\frac{1}{c} + \frac{rl}{\mu_p}} \frac{1}{\mu_{sg}} \quad (11b)$$

$$\frac{\partial i_p}{\partial e_{bb}} = \frac{1}{\frac{1}{c} + \frac{rl}{\mu_p}} \frac{1}{\mu_p} \quad (11c)$$

$$\partial i_p = \frac{1}{\frac{1}{c} + \frac{rl}{\mu_p}} \left(\partial e_g + \frac{\partial E_{sg}}{\mu_{sg}} + \frac{\partial E_{bb}}{\mu_p} \right) \quad (12)$$

when rl/μ_p is small compared with $1/c$,

$$\partial i_p \approx c \left(\partial e_g + \frac{\partial E_{sg}}{\mu_{sg}} + \frac{\partial E_{bb}}{\mu_p} \right) \quad (13)$$

The above equations hold for all tubes whose characteristics can reasonably be described by equation 10a in the general region of the end of the load line for electrode voltage variations of a few per cent; i.e., ∂e_g, $\partial E s_g$ and ∂E_{bb}. If the tube is a triode, equation 11b is omitted, and the corresponding term is dropped from equations 12 and 13. From these equations one can determine the maximum variations permissible for e_g, E_{sg} and E_{bb} for a given maximum dip or the change in the total load current diL which is rl dip. Since the screen-grid amplification factor is usually of the order of 5, regulation of this voltage will probably be necessary in most cases. With tetrodes it is possible to "correct" the screen-grid voltage for changes of plate voltage, a practice that may be simpler than regulation of the plate supply voltage.

The power supply voltage may vary because of changes in either the ac input voltage to the pulser or changes in the dc average current from the power supply. The change in average current may be brought about by variations in the duty ratio that occur as a result of changes in either the pulse duration or the pulse recurrence frequency, or both. Variations of the ac line voltage input to the pulser causes a change in all the voltages in the pulser, and therefore changes the bias voltage as well as the other factors in equations 10 and 12. In order to make a complete analysis it would be necessary to consider the effect of bias changes, effects caused by the partial discharge of coupling capacitors, and current build-up in shunt inductances across the load. Another factor to be considered would be the regulation of the driving pulse supply, i.e., the effect of the internal impedance of the driving pulser due to variations in grid current of the following stage as drive is varied from C to A.

In order to compare the operation of tubes both above and below the knee of the curve, the effect of one variable, the plate voltage or E_{bb}, on the plate or load current will be investigated. To simplify the problem we will consider a triode. In the equations developed below $\left(e_g + \frac{E_{sg}}{\mu_{sg}}\right)$ can be substituted for e_g to cover the case of a tetrode. This problem is of interest in the operation of magnetrons since the magnetron frequency shifts as its current changes, i.e., the "pushing figure," df/di.

For a triode operating above the knee of the characteristic curves, equation 11c can be divided by equation 10b omitting the term E_{sg}. These equations give

$$\frac{dip}{i_p} = \frac{1}{1 + \frac{\mu_p e_p - E_S}{E_{bb}}} \frac{dE_{bb}}{E_{bb}} \quad (13)$$

For a triode operating below the knee of the curve, equation 10a reduces to

$$i_p = \sigma e_p = \partial \left(E_{bb} - \partial E_S - i_p\, rl\right)$$

which gives,

$$\frac{dip}{i_p} = \frac{1}{1 - \frac{E_S}{E_{bb}}} \frac{dE_{bb}}{E_{bb}} \quad (14)$$

In order to compare magnetron operation under the two conditions, consider the 725A magnetron which is to be operated at 11 KV and 10 amperes. Under these conditions E_S will be 9700 volts. For a 4PR60 tube operating below the knee of the curve, the plate voltage, E_{bb}, will be 11.7 KV, the screen-grid voltage is taken as 1250 volts, e_g will be 0. According to equation 14,

$$\frac{dip}{i_p} \approx 6 \frac{dE_{bb}}{E_{bb}}$$

For operation above the knee of the curve, constant grid voltage drive curves are drawn tangent to the characteristic curves for $e_g = 0$ and -50 volts at $e_p = 2000$ volts. E_{bb} will be 13 KV, $e_g = -35$ volts, $\mu_{sg} = 4$, $\mu_p = 70$ and

$$\frac{dip}{i_p} \approx 0.55 \frac{dE_{bb}}{E_{bb}}$$

From these results it is apparent that the regulation in plate current due to variations in E_{bb} is improved by a factor of 10 when the operating point is above the knee as compared to operation below the knee. Of course for operation above the knee, it is necessary to regulate e_g and E_{sg}. If the load had been a pure resistance, i.e., $E_s = 0$, the comparative values are reduced to 1 and 0.4 or a ratio of 2.5 instead of 10.

(Continued on Page 37)

Editor's Note:

CATHODE PRESS is pleased to reprint here an article on a topic of considerable interest: cable sheathing by electronic means. A recent development, in a relatively new field, electronic high frequency resistance welding, has been reported previously by CATHODE PRESS (Vol. 15, No. 1, 1958). The Thermatool process, as this high frequency resistance welding is known, employs induction heaters which use the Machlett ML-6696 coaxial terminal triode.

Acknowledgment:

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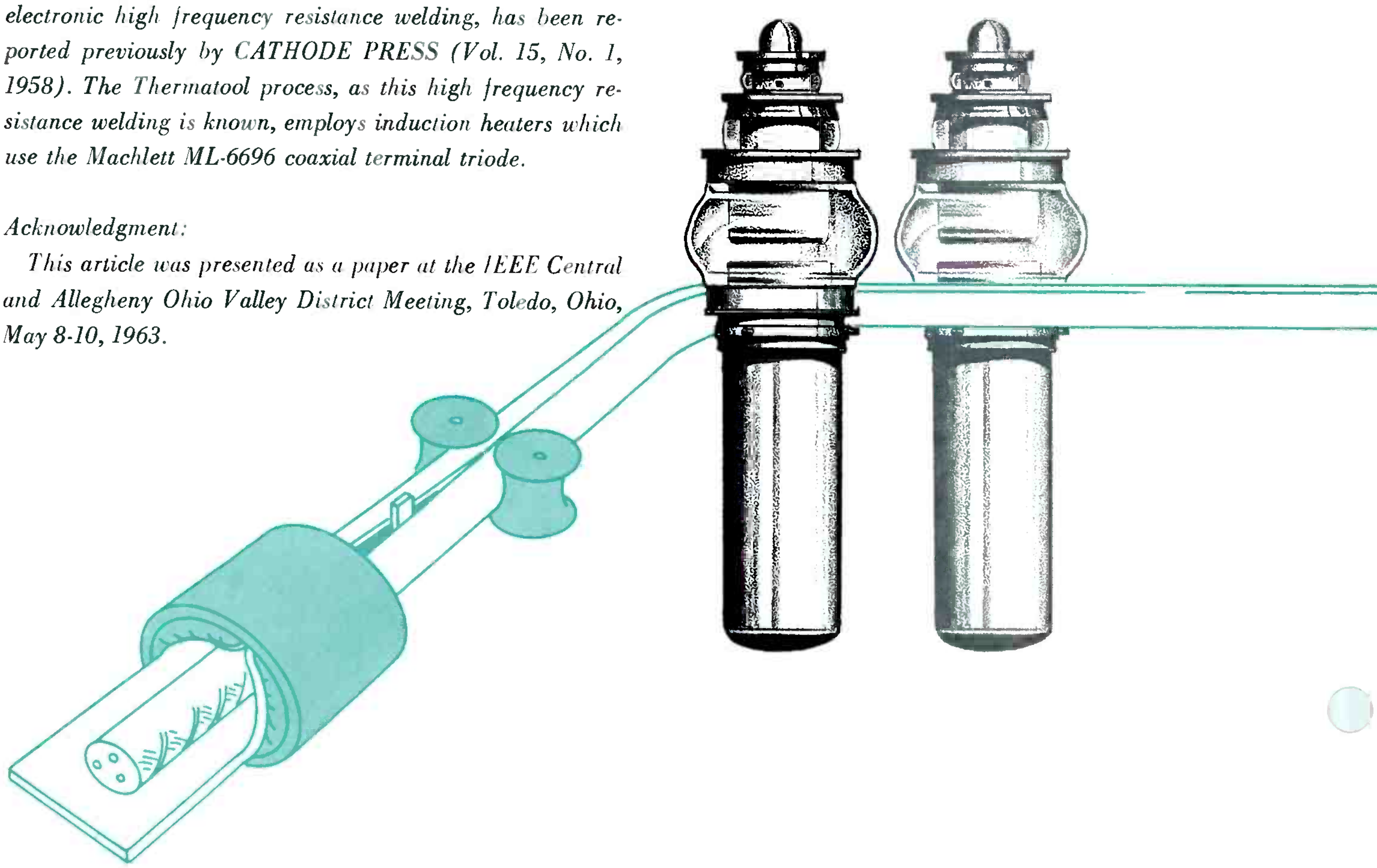

Thermatool Corporation, New Rochelle, New York, a subsidiary of the American Machine and Foundry Company, has developed a new method of applying metal sheaths to power and communications cables. This method is an outgrowth of Thermatool's widely used high frequency resistance seam welding process for metal tubes and pipes. Interestingly, the first production installations of this novel process have been in Europe, rather than the United States. The purpose of this paper is to describe the electrical features of this new cable sheathing process.

Cable Sheathing Materials

Lead and aluminum have been used traditionally for sheathing cables. Lead has the advantage that it is relatively easy to extrude. In addition, its extrusion temperature is not so high that it damages the cable insulation. It is possible to extrude lead cable sheath continuously. But lead is heavy and soft. Its dimensional stability over long periods of time is not ideal.

Aluminum makes a better cable sheath than lead. It has superior physical properties and is, of course, much lighter. However aluminum is more difficult to extrude. Both the pressure and the temperature required are higher than for lead. Special provision must be made when extruding aluminum around an insulated cable to avoid damaging the insulation. Continuous extrusion of aluminum cable sheathing has not proven commercially practical. Of course this limits the length which can be made at one time, determined by the amount of material in a single billet. It is possible to sheath cables with aluminum by first making an empty aluminum tube and then drawing the cable into it. But thin-wall aluminum tubes are difficult to handle without kinking and damaging. Furthermore the continuous length possible by this method is again limited.

Advantages of Method

The high frequency resistance welding process of sheathing cables which was developed by Thermatool elimi-

Cable Sheathing by High Frequency Resistance Welding

By C. A. TUDBURY,
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nates the disadvantages of the older methods. Not only can cables be sheathed in any desired length, but also with any desired material. Copper and stainless steel, for instance, possess properties which are outstandingly favorable for cable sheath. Certainly these materials could not be applied to an insulated cable by extrusion, but they can be by the new process.

Skin Effect

Thermatool's process for cable sheathing utilizes two phenomena which have been usually considered as undesirable by most electrical and electronic engineers. These are skin effect and proximity effect. Skin effect is the tendency of alternating current to be more concentrated at the surface of a conductor than inside the conductor. The degree of skin effect depends upon four factors: frequency, conductor conductivity, permeability, and size. Increasing any one of these quantities will cause skin effect to be more pronounced. Skin effect is present to some degree in every alternating current circuit, as illustrated in Figure 1. Most engineers regard skin effect simply as a phenomenon which increases the resistance (and therefore the losses) in a conductor carrying alternating current. But, as will be illustrated in more detail later, skin effect is a desirable and essential adjunct of high frequency resistance welding.

It is customary to express the degree of skin effect numerically by using a quantity known as reference depth (sometimes called skin depth). The ratio of conductor diameter to reference depth is a measure of degree of skin effect, the effect being more pronounced when this ratio is large. If the conductor is rectangular, the ratio of the smaller dimension to reference depth is significant. When this ratio is equal to or greater than 10, skin effect is very pronounced. A solid conductor then has substantially the same resistance as a hollow conductor of the same outside dimensions and with a wall thickness equal to reference depth.

A complete discussion of the theory of skin effect is outside the scope of this paper, but it is interesting to display the equation for reference depth, which is

$$d = 3160 \sqrt{\frac{\rho}{\mu f}}$$

where, d = reference depth, in inches
ρ = conductor resistivity in ohm-inch
μ = conductor relative permeability
f = frequency in cycles per second

For aluminum at room temperature, and with a frequency of 450 KC (which is what is commonly used for high frequency resistance welding), reference depth is approximately .005 inch.

Proximity Effect

The second phenomenon upon which high frequency resistance welding of cable sheaths relies is proximity effect. Proximity effect manifests itself when two conductors in which skin effect is very pronounced form a go and return circuit, and are located physically close to each other. Actually they must be close enough so that the external magnetic field which they set up is appreciably more concentrated between them than elsewhere. This causes the magnetizing force to be greater between them than elsewhere. As a result the current, already flowing in a thin surface layer because of skin effect, rearranges itself over the surface of the conductors in such a way as to supply the higher magnetizing ampere-turns per inch required for the restricted space between the conductors. When skin effect and proximity effect are both pronounced, substantially all the current flows along the opposing edges of the conductors, as illustrated in Figure 2a. The effect can be even further enhanced by the addition of a magnetic core which serves to increase the ratio of magnetizing force between the conductors to the magnetizing force elsewhere, as in Figure 2b.

High Frequency Resistance Welding

High frequency resistance welding of metal cable sheath is illustrated schematically in Figure 3a. The sheath is formed from flat strip in a special die-forming mill (not shown). The open seam passes continuously beneath a pair of sliding contacts. High frequency current is introduced through one

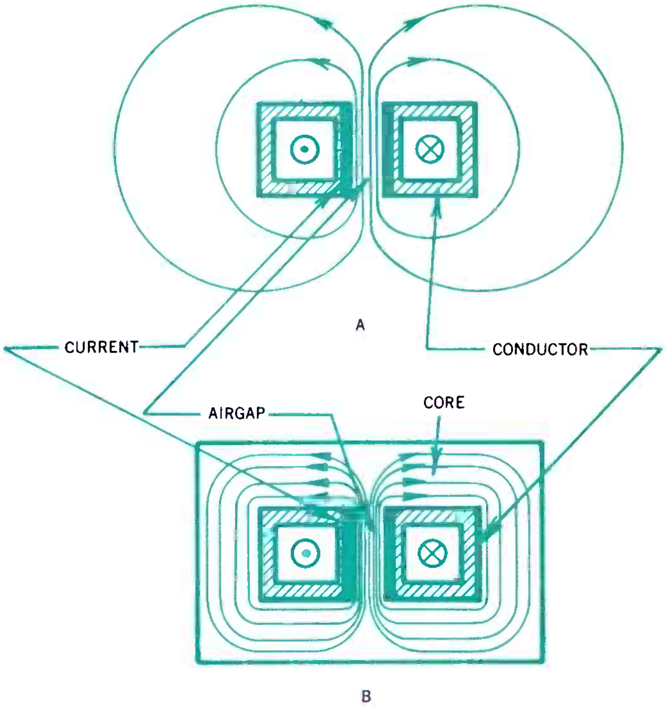


Figure 2 — Proximity effect in go and return circuit.

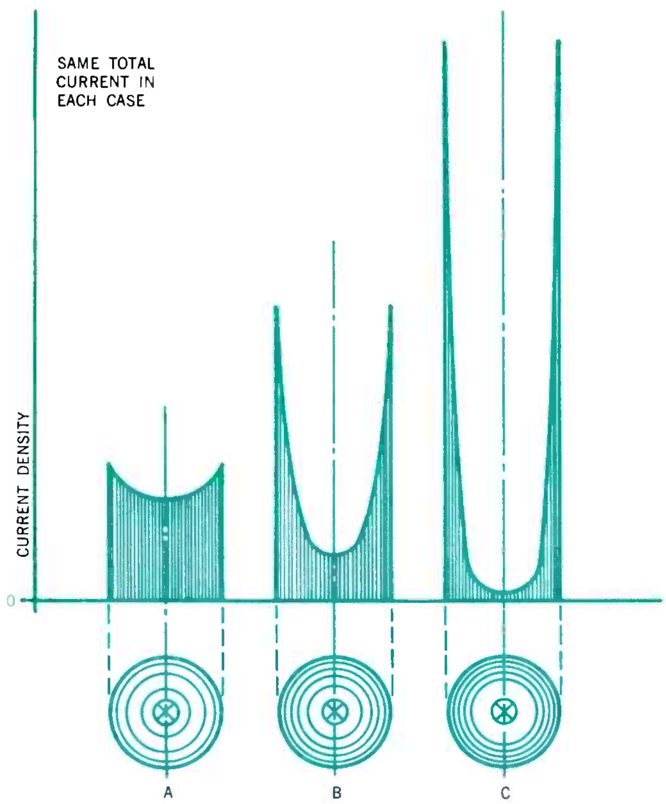


Figure 1 — Various degrees of skin effect.

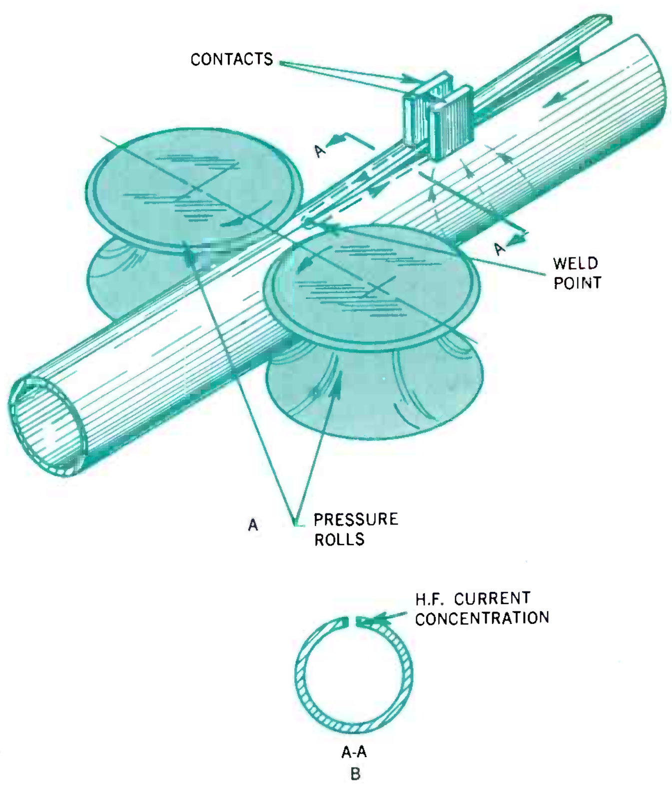


Figure 3 — High frequency resistance tube welding.

of these contacts, and flows (because of skin effect and proximity effect) along the strip edge to the point, slightly upstream from the pressure rolls, where the opposing edges come together. The current returns to the other contact along the other edge of the "vee"-shaped opening.

The high frequency current traversing the edges of the "vee"-shaped opening is compressed into a small cross sectional area, as illustrated in Figure 3b, and the resistance which it encounters is high. The result is rapid heating of the edges of the strip, with negligible heating elsewhere. This is best illustrated by a numerical example. Assume that the cable sheath is to be made of aluminum strip, .030 inch thick, and that the frequency is 450 KC. Reference depth will therefore be approximately .005 inch. Assume also that the RMS value of the current is 1000 amperes. Under these conditions, the resistance is the same as if the entire current of 1000 amperes were flowing with uniform current density in an aluminum conductor whose cross section is .005 inch by .030 inch. Heat will be developed by I^2R at a rate of approximately 7.5 KW per linear inch.

With power of this order of magnitude developed in the strip edges, their temperature rapidly rises to welding temperature as they traverse the relatively short distance from the contacts to the closure point. The hot edges are pressed together by the pressure rolls. A forge type weld results which is physically sound, as well as pressure tight.

There is a second path which high frequency current can traverse from one contact to the other, illustrated by the dotted lines in Figure 3a. This path, around the back of the tube, is not only widely spread out, but also has a higher inductance than the path along the narrow "vee" gap. The net result is that the portion of the contact current which goes around the back of the tube is not only small, but also causes very little heat loss.

Production Rate

A typical production rate when welding .025 inch thick aluminum sheath using a 60 KW 450 KC Thermatool electronic generator is 60 to 70 feet per minute (FPM). It is interesting to note that the faster the rate, the better is the efficiency. At 60 FPM, and assuming that the contacts are one inch upstream from the "vee" apex, it takes a spot on the strip edge only .0833 second to traverse the "vee" and be heated. But the temperature differential between the edge and the remainder of the strip is so great that even in this short interval of time an appreciable amount of heat travels away from the edge by conduction. If the rate of travel were to be doubled, the power would not have to be quite doubled, as there would be less time for heat to be conducted away. Higher welding rates have the further advantage that the material behind the edges is colder and stiffer, which causes the pressure rolls to be more effective.

Mechanical Features

Although this paper has to do primarily with the electrical aspects of cable sheathing by high frequency resistance weld-

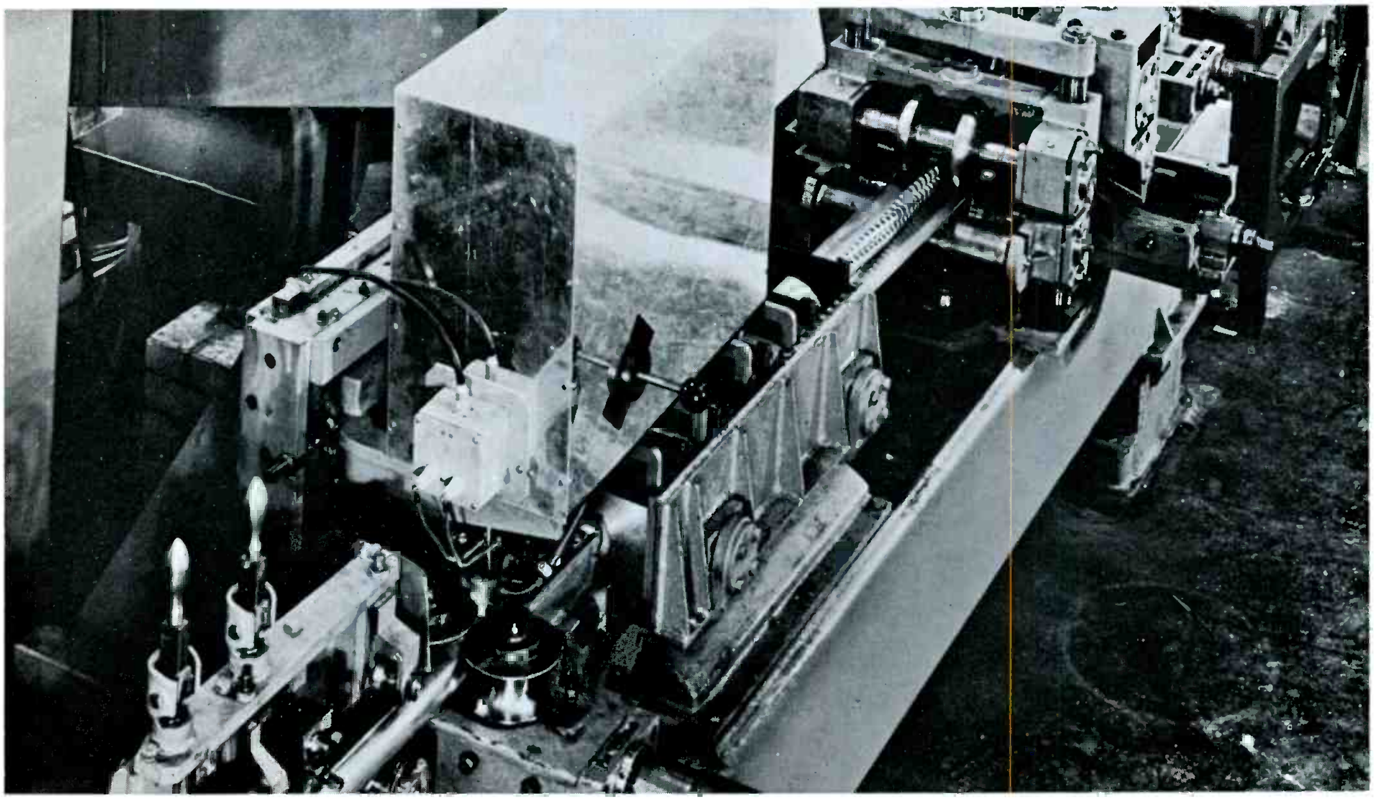


Figure 4 — High frequency cable sheathing mill.

ing, a word or two about the mechanical features is appropriate. Most tube and pipe forming mills utilize solid forming rolls. In successive stands, they gradually form flat strip into a circular shape with an open seam. Thermatool welding units are in production the world over on this type of mill, making tubing and pipe. Sizes range from one-half inch or less to three feet in diameter, and wall thicknesses is from a few thousandths to a half inch. The high frequency electronic generators range in output rating up to 560 KW.

When welding cable sheathing while the cable is inside, it is not practical to utilize solid rolls for the forming. The rolls and the cable cannot be in the same place at the same time. Therefore a die-forming mill, shown photographically in Figure 4, was developed. This enables the strip to be formed into tubular shape while the cable is inside, travelling forward at the same speed as the strip.

After the die-forming section of the mill, and just ahead of the sliding high frequency contacts, there is a seam guide. Its function is to ensure that the open seam between the strip edges is in proper registration relative to the contacts and also to ensure that the "vee" shaped opening between the contacts and the weld point has the optimum angle of opening. The seam guide is made of wear resistant material. For cable sheathing applications it is usually of the sliding type, and is insulated so as not to provide an additional electrical path between the contacts.

Downstream from the weld point, there is a tandem pair of scarfing tools which remove the external bead. There is also a thin device inside the tube between it and the cable which mechanically smooths the slight internal bead. At the weld point, the inside diameter of the sheath is usually about one-eighth inch larger than the outside diameter of the cable. This enables the welding operation to be accomplished without heat-damaging the insulation. Immediately after welding, therefore, the sheath is in the form of a loose metal tube surrounding the cable. But its diameter relative to the cable is such that it suits the subsequent corrugating operation, permitting the valleys of the corrugations to be pressed firmly against the cable. Corrugating is sometimes a separate operation and sometimes is performed continuously as the cable and sheath emerge from the forming and welding mill.

Electronic Equipment

Most high frequency resistance welding installations for cable sheathing utilize 60 KW Thermatool electronic generators. Basically these are class "C" oscillators housed in rugged steel cabinets for industrial service. They feature hermetically sealed rectifier transformers, a capacitive voltage divider feedback circuit for grid drive, complete voltage regulation, filtering of rectifier output, and a power control device which permits the operator to alter the power steplessly even while the unit is operating.

The weld head (Figure 5), which is mounted on the cable sheathing mill, consists of a high frequency step-down transformer, its secondary leads, and the welding contacts. The stepless power control device, referred to previously, is an integral part of the secondary leads. One lead includes a one-turn series loop. A cylindrical member containing magnetic core material at one end and a copper slug at the other can be moved in and out of this loop by the operator by means of a handwheel. Continuous power control is thereby available from a minimum when the magnetic end is in the loop to a maximum when the copper end is in the loop.

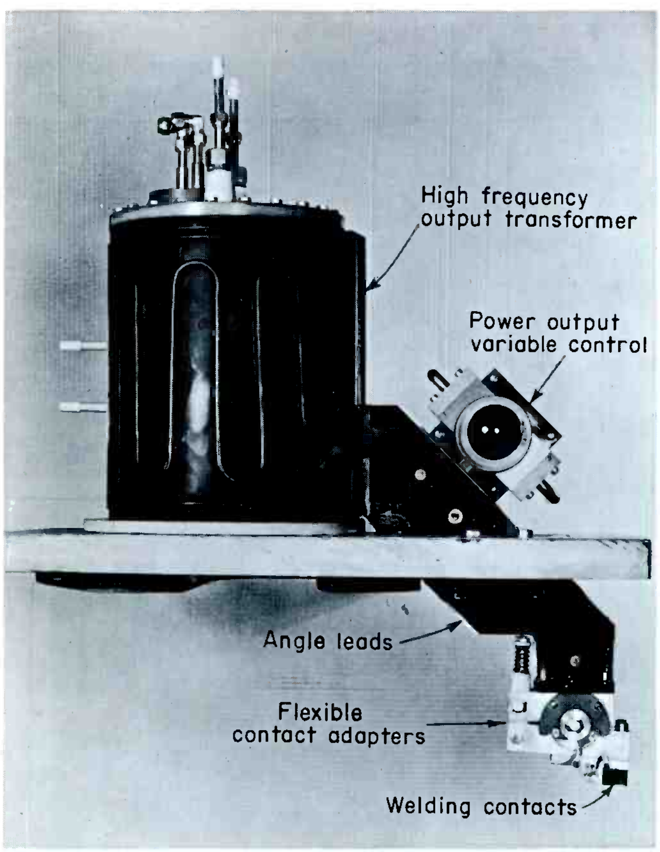


Figure 5 — Welding head.

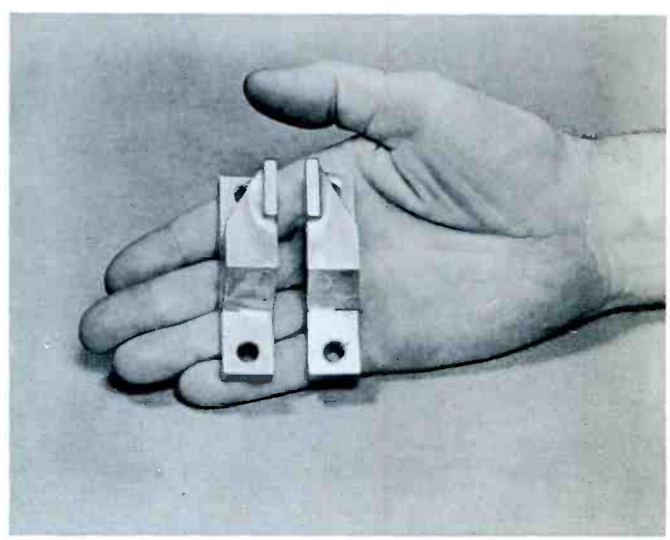


Figure 6 — High frequency resistance welding contacts.

The sliding contacts (Figure 6) are surprisingly small, considering the fact that they handle 60 KW at low voltage. They feature replaceable tips which can be replaced by a simple brazing operation after they are worn out. Average life of a set of tips is 50,000 feet of sheath or more. The contact bodies are water cooled. The cooling water is supplied through the secondary leads by means of a quickly made connection utilizing O-rings.

Future Developments

The next step in the development of this process will probably be mechanical. It will involve the development of methods for forming larger diameter thin-wall metal sheaths while still keeping the edges in proper registration and at the same time providing adequate welding pressure. (The edges of large diameter thin-wall tubes are prone to lap over each other when squeeze roll pressure is applied).

The future holds great promise for this process. As is the case in many new developments, conservative companies in the U.S.A. have hesitated, while their counterparts in Europe have gone ahead. It is anticipated that before long, high frequency resistance welded cable sheathing will be an established industrial process on both sides of the Atlantic.

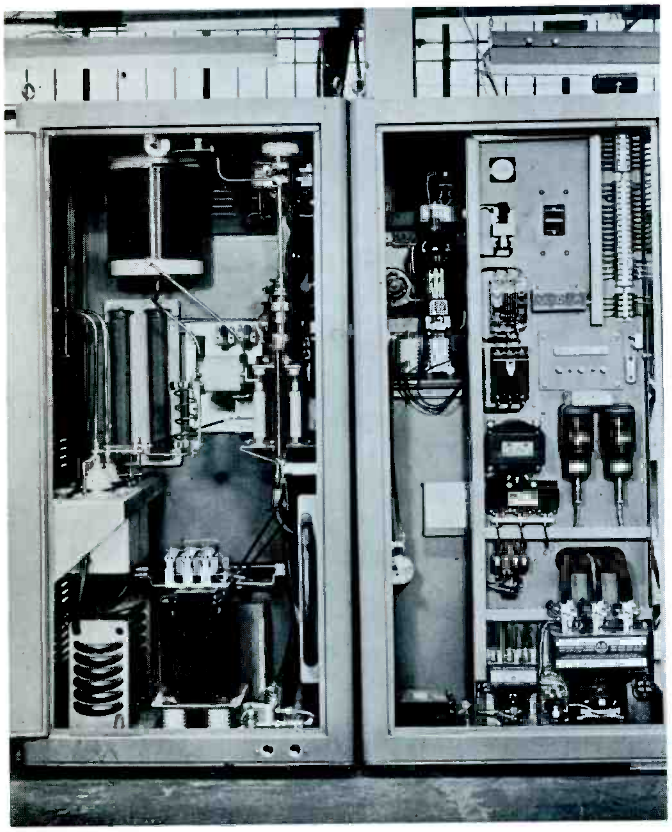
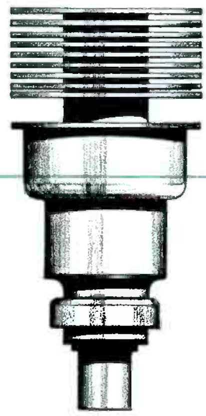


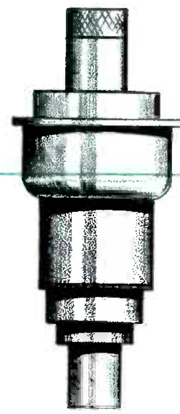
Figure 7 — View of 60 KW Thermatool High Frequency Generator, Model VT-60 with ML-6696 visible in rack to left.

Operating conditions of final amplifier tubes of the Thermatool induction heaters, VT-60 (1 — ML-6696) and VT-140 (2 — ML-6696's), employed for high frequency resistance welding:

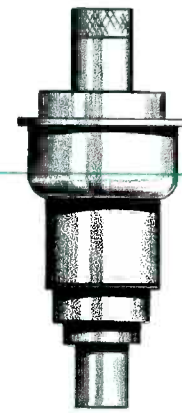
ML-6696

Frequency	450 Kc
Plate Voltage	11.7 kv
Plate Current	9.0 a
Grid Voltage	—1500 v
Grid Current	0,6 a





The Reliability of the Machlett Planar Triode



by NELLO ZUECH
Senior Production Engineer,
Small Power Tube Product Line,
The Machlett Laboratories, Inc.

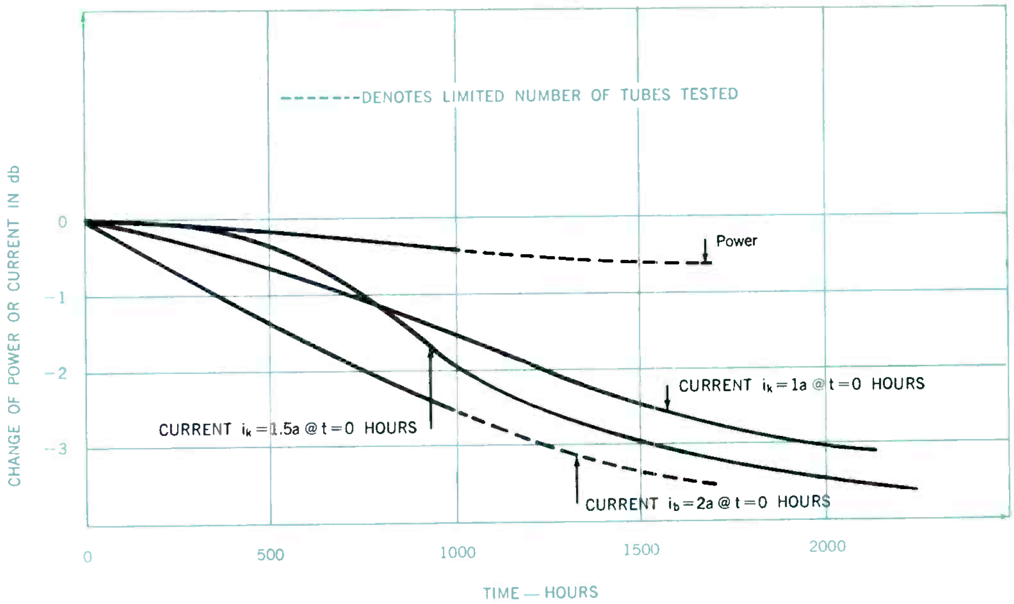
Much has been said in recent years about system reliability. The military, and therefore, industry has become reliability conscious. Since a system can exhibit a reliability only as good as the reliability of its least reliable component, the reliability of the electron tube aside from other components has come into question.

Unfortunately, planar tubes, like all tubes, are severely influenced by their environment, with respect to circuitry as well as ambient conditions. Because of this, it might be argued that the data upon which tube reliability figures are based, only reflect the reliability of the particular tube type, in the particular equipment specified, under a particular set of conditions. The truth of this will no doubt be debated many times over in the coming years. Nevertheless, if the conditions to which the tube is subjected during life test are more severe than normal or can be considered representative of the average application for which the tube was intended, the reliability data so obtained can be extrapolated to be meaningful for most field conditions.

The actual life test conditions to which a tube is subjected are governed in many cases by the pertinent military specifications. The philosophy upon which these conditions are based is generally in a state of flux. Recent emphasis is being placed on the filament stand-by life test for planar tubes, its proponents noting its success in its application on larger more expensive tubes as well as observations that this type of test is at least as rigorous, if not more detrimental than, rf life tests, provided the conditions have been properly chosen. Also in its favor is the argument that not all applications require continuous rf operation, and a large number are operating in a stand-by position often at a reduced filament voltage. Thus far, it has been the experience at Machlett, with respect to the ML-7698 and ML-7815, that the filament stand-by type of life test is more severe, perhaps as a result of the end point criteria (described later in this article), and results in a higher failure rate than would be the case under rf operational conditions.

What constitutes a failure? Either of two factors, as defined in military specifications: the inability of the tube to function, or the inability of the tube to meet certain predetermined test conditions. Consequently, while in a laboratory a tube may fail, that same tube in a field application under which the tube is not handled or disturbed once it is put in a socket, should give a longer life. Hence, reliability figures based on laboratory life tests can actually be considered pessimistic, provided the consumer has taken the necessary precautions to ensure against catastrophic or premature failure due to external circumstances.

The more familiar failure modes of planar tubes are essentially: (1) — emission failures due to cathode poisoning or cathode exhaustion at end of life, or (2) —catastrophic; that is, shorting between elements, filament defective either open or short, overloaded grid or anode due to operation in excess of ratings (either with the knowledge of the user or inadvertently as in the case of a failure in auxiliary equipment which is reflected back into the tube); leakers or loss of



vacuum due to extreme environmental conditions or to overheating because of improper cooling or of operation in excess of rating, and random failures which are virtually impossible to control.

Before proceeding, the following definitions should be embedded in the mind of the reader:

Reliability[1] — The probability that a device will perform as intended under design conditions for a specified period of time.

Confidence level[2] — The probability of rejection of material conforming to the specified failure rate. 90% confidence means certainty to 90% that the true mean time between failures is greater than the calculated limit and the true failure rate is less than its limiting value.

Failure rate[3] — The failure rate is expressed in terms of failures per unit of time. It is computed as a simple ratio of the number of failures f, during a specified test interval, t, to the total or aggregate survival test time of the articles undergoing test during the test interval:

$$r = \frac{f}{T}$$

MTBF[3]— Mean time between failure — During the operating period when the failure rate is constant, the MTBF is the reciprocal of the constant failure rate, or the ratio of the total operating time to the total number of failures:

$$m = \frac{1}{r} = \frac{T}{f}$$

There are essentially three rates of failure during the life of most components. Early in life failures, referred to as "infant mortality," period of constant failure rate, and wear-out phase period. Because of the nature of electron tube processing "infant mortality" is all but eliminated. And since most often a tube gives warning of impending failure by a change in operating characteristic making replacement at a somewhat predetermined time possible, all reliability data is generally based on a constant failure rate. This constant failure rate is further based on the assumption that the design is essentially constant and that a uniform manufacturing process is maintained. Assuming a constant failure rate in turn implies an exponential, or Poisson distribution of failures, namely:

$$R = e^{-\frac{T}{m}}$$

T — total operating time, m-MTBF, and R — reliability.

In the following tables for the individual tube types, two sets of failure rates are determined, one for a confidence factor of 90% — based on the recommendations of the Darnell report[9] — and one for a confidence factor of 60% — based on the recommendations of the Electronic Industries Association (EIA)[2]. Also included in the tables wherever possible are failure rates which are arrived at from data fed back from the field. As can be seen from the tables, the failure rates arrived at in the laboratory are, for the most part, in agreement with, or at least of the same order of magnitude as those based on information fed back to Machlett from various field applications. In other words, the failure rates are indeed realistic and the degree of reliability claimed is attainable.

High levels of reliability can be assured provided proper choices are made with respect to tube types and operating conditions. Because of the interrelationship between tube and cavity, effort should be expended to mate the two for optimum operation. Once the tube has been placed in the socket, it should be handled as infrequently as possible. Envelope and seal temperatures should be maintained at less than 175 degrees C[4], even though the tubes can actually withstand seal temperatures up to 250°C. Heater voltage should be at most at maximum rating and, if possible, optimized for the particular conditions (above 500 Mc transit time back-heating starts to have an effect). It has been shown on one Machlett tube type that life can be increased at least two and a half times by operating the filament at 5% below versus 5% above rating. In addition to optimizing, the filament voltage must be regulated to preferably 2% or better. Excessive plate dissipation should be avoided. Vibration should be held to a minimum.

If all the above precautions are taken there is no reason not to believe the reliability data is not valid and that the failure rates can in actuality be exceeded.

EXAMPLES OF CALCULATIONS[11]

Confidence bounds for the MTBF and failure rate for any given set of data may be estimated by various methods.

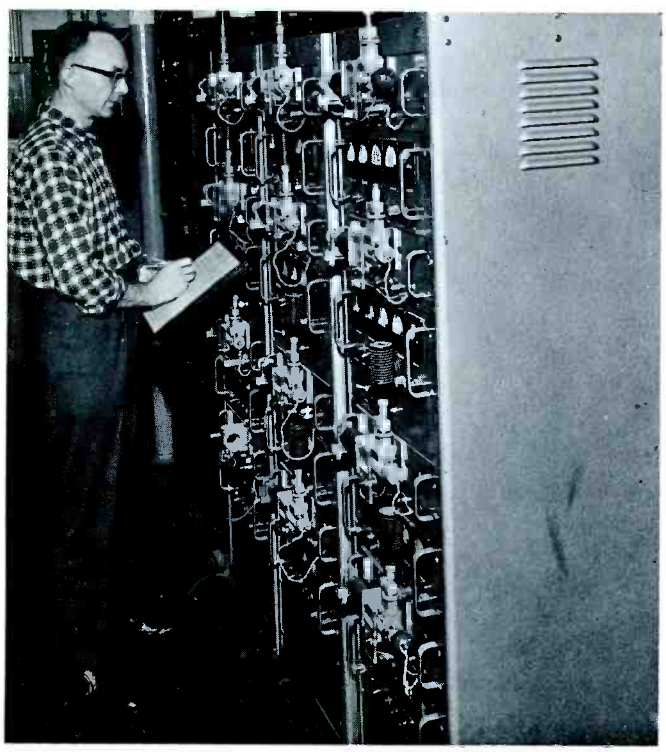


Figure 1 — Multiple unit life test equipment for ML-6442; contains plate pulse cavity oscillators. Test parameters: Pulsed Oscillation F = 3450 mc minimum; e_{py} = 3000 v; $R_g/1b$ = 2.5 mode; tpv = 1.0 usec ±10%; trv — 0.1 usec., maximum; tfr = 0.2 usec, maximum; prΩ/Du = 0.001 ±5%; E_f = 6.0 V.

Thus, the Poisson, the χ^2, or the F distributions, all well known to statisticians, may be used to calculate the confidence limits.

Example 1:

Given a total tube-hours of test equal to 100,000, with 2 failures; (a) what is the best estimate of failure rate? (b) what would be a failure rate limit which would include 90% of failure-rate estimates made under the same sampling conditions?

(a) $$\text{MTBF} = \frac{100{,}000}{2} = 50{,}000 \text{ hours}$$

$$\text{Failure rate} = \frac{1}{\text{MTBF}} = \frac{1}{50{,}000} = 0.00002$$ failures/hour or 2% failures/1000 hours.

These are "most likely," or modal estimates.

(b) *Using Thorndike Chart.*

Since we have made the assumption that the failure rate is constant this implies an exponential, or Poisson distribution of failures. We can therefore use Poisson tables or charts to place confidence limits on our estimates. (1)

The Poisson parameter in our case is $\frac{T}{\text{MTBF}}$, where T is total test hours.

If we look up the Poisson parameter on a Thorndike chart (2) for the 10% probability of occurrence of $c = 2$, or less, defectives, we find $pn = 5.3 = \frac{T}{\text{MTBF}}$.

Then, $$\text{MTBF}_{(.90)} = \frac{T}{5.3} = \frac{100{,}000}{5.3} = 18{,}900 \text{ hours}$$

and, $$\text{F.R.}_{(.90)} = \frac{1}{\text{MTBF}} = \frac{5.3}{100{,}000} = 0.000{,}053$$ failures/hour, or 5.3%/K hours.

We use the 10% probability point, since we want to be 90% certain that the true MTBF is greater than our calculated limit and the true failure rate is less than its limiting value.

Using Poisson Tables

We may choose to use a table of culmulative Poisson probabilities, such as Table II of Molina's Tables. (3) The Poisson parameter in these tables is denoted by a, and the probabilities are for *c or more* defectives occurring. Since we want to pick a limiting value of α, such that the number of defectives $r = 2$ or less will occur only 10% of the time, we look through the table for $c = r + 1 = 2 + 1 = 3$ defectives until we find the cumulative probability of a for 90%, $c = 3$. This value is approximately 5.3. Values for $\text{MTBF}_{(.90)}$ or $\text{F.R.}_{(.90)}$ are then found as in the calculations under the Poisson Chart above. We are then confident that the true MTBF under the same conditions will be equal to, or greater than, our limiting value of $MTBF_{(.90)}$, 90% of the time.

χ^2 Solution

If we conclude our testing after some time T total tube-hours, a one-sided 100 (1-α) confidence interval for MTBF is given by the expression (4) (5)

$$MTBF_{(1-\alpha)} > \chi^2_{\alpha(2r+2)}$$

then, T = 100,000 hours (given)

r = 2 failures (given)

α = 0.10, since desired confidence 90% = 100 (1-χ)

$\chi^2_{\alpha\,(2r+2)}$ is the upper 10% of the χ^2 distribution for 2r + 2 degrees of freedom. χ^2 tables are found in most recognized statistical texts.

$$\chi^2_{.10(6)} = 10.6$$

Substituting in the formula,

$$MTBF_{(.90)} = \frac{2 \times 100{,}000}{10.6} = 18{,}900$$

hours

$$\text{and, } F.R._{(.90)} = \frac{1}{MTBF_{(.90)}} = \frac{1}{18{,}900}$$

hrs. = 5.3%/K hours, which checks with the values found by using Poisson tables or charts.

Example 2:

100,000 tube-hours are achieved on a particular test, with no failures. What is the MTBF? The MTBF cannot be calculated in the usual manner, since $\frac{100{,}000}{0}$ is unsolvable because of the zero in the denominator. However, a median estimate (50% confidence) can be found, using the χ^2 formula in Example 1, and a value of χ^2 for 50%.

2r + 2 2 (0) + 2 = 2 degrees of freedom

$$\chi^2_{.50(2)} = 1.39$$

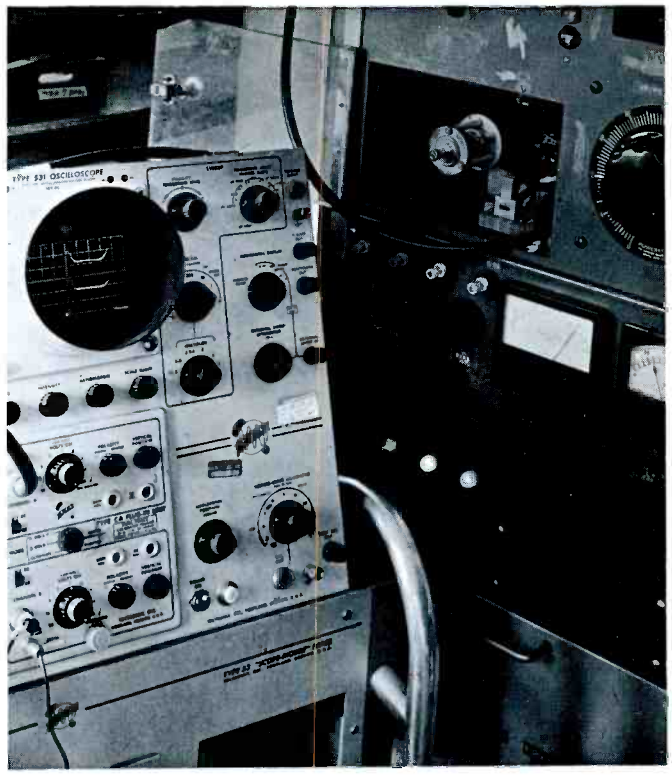


Figure 2 — View of End Point Test Set for ML-7815 and ML-7698; evaluates the deteriorating effect of filament standby life test by measuring the reduction in peak anode current under drive conditions established at 0 hours.

$$MTBF_{(.50)} = \frac{2 \times 100{,}000}{1.39} = 144{,}000 \text{ hours}$$

The median estimate of MTBF may also be found from the approximate relationship

$$MTBF = \frac{\text{total tube-hours}}{r + 0.693}$$

$$\text{Thus, } MTBF = \frac{100{,}000}{0.693} = 144{,}000 \text{ hours.}$$

We can of course calculate confidence limits at any desired level, using one of the methods suggested in Example 1 (b).

REFERENCES

[1] Allen, Gerald F., "Reliability Slide Rule," *Electronics*, September 6, 1963, p. 44.

[2] Finochi, Anthony J., "Ramifications of PSMR-1, the Darnell Report," *Electronic Products*, August 1962, p. 69.

[3] Calabro, *Reliability Principles and Practices*, McGraw-Hill, 1962.

[4] Henry, Robert S., "Thermal Design for Reliability," *Electro-Technology*, May, 1962.

[5] *Machlett UHF Planar Triodes* (Brochure), p. 16.

[6] Proposed Military Standard, "Life Qualification and Sampling Procedures for Use in Electronic Component Part Established Reliability Specifications" (Project Misc-0229) 11 March 1963.

[7] Edward, M. W., et al, *Subminiature Electron Tube Life Factors*, Reinhold Publishing Co., Elizabeth, N. J., 1961.

[8] Rath and Strong, "Notes on a Reliability Seminar."

[9] Parts Specification Management Report (PSMR-1), Department of Defense, May 1960.

[10] *Aero Geo Astro Reliability and Confidence Slide Rule Handbook*, October 1962.

[11] *Industrial Military Tube Reliability Data Report No. 3*, Raytheon Company, Industrial Components Division.

NOTE: Reliability Life Test Reports for ML-7289, ML-7815, ML-7698, and ML-6442 follow on Pages 30, 31, 32 and 33 respectively.

DATE ISSUED: 12/1/63

REPORT NO.: 1

SUMMARY OF TEST RESULTS	*No. Tested*	*Total Tube Hours*	*No. Failed*	*Failure Rate in % Per 1000 Hours Confidence Factor 60%*	*90%*
Total Failures — Electrical and Catastrophic — (2100 MC Life Test)	81	32,393	1*	< 6.1	< 11.9
Total Failures — Electrical and Catastrophic — (500 MC Life Test)	121	73,932	0	< 1.24	< 3.1

*Catastrophic-Leaker at 1791 Hours

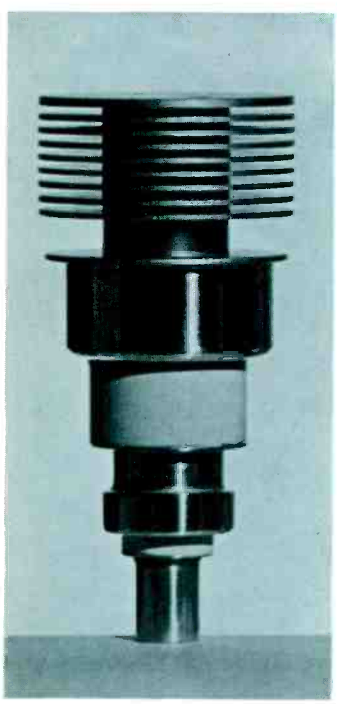
TEST DESCRIPTION: Per MIL-E-1/1120B

2100 MC: **Group C,** F = 2000 Mc Min;
Ebb = 1000 Vdc; Ib = 90 madc;
Ef = 5.0 Vac; initial Po = 15W Min.
Time = 200 Hours
ΔPo — 25% Maximum
Pulse Emission (2) Δi_k = 120 ma Max.

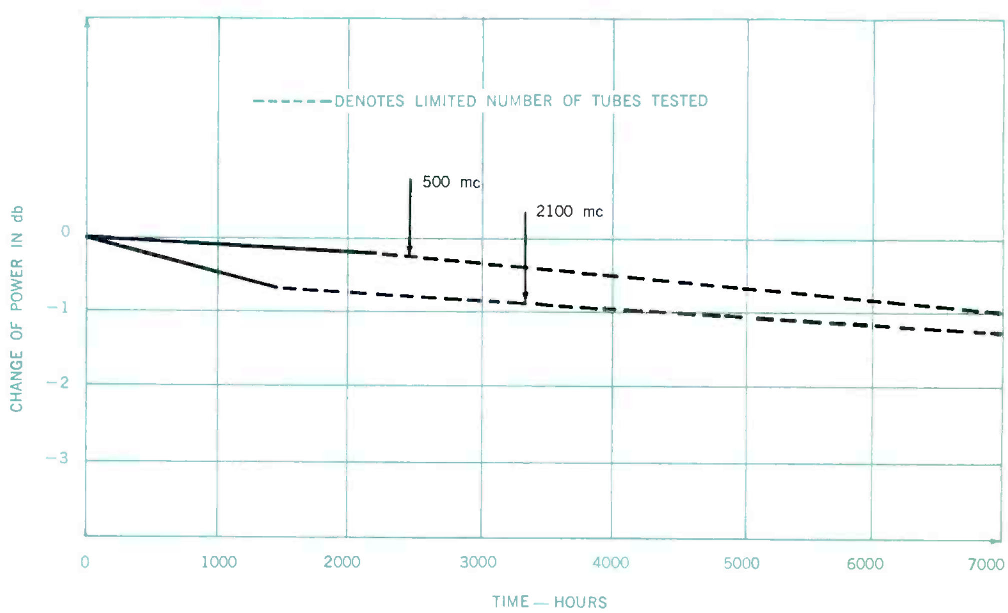
500 MC: **Group C,** F = 500 Mc Min;
Ebb = 800 Vdc; Ib = 80 madc;
Ef = 6.0 Vac; initial Po = 27W Min.
Time = 500 Hours
ΔPo — 25% Maximum
Pulse Emission (2) Δi_k = 120 ma Max.

APPLICATIONS: The ML-7289/3CX100A5 is a ruggedized, high-mu, Planar Triode of ceramic and metal construction designed specifically for use in equipment as an oscillator, amplifier or frequency multiplier at frequencies up to 2500 mc. It is well suited for pulsed operation at frequencies up to 3000 mc.

REMARKS: See Cathode Press Vol. 15, No. 1, 1958, "The Life and Times of the 2C39 in Microwave Radio Relays," P. 25.
Cathode Press Vol. 20, No. 1, 1963, "Atlantic Pipeline Company: Microwave User Since 1949," P. 25.
Based on these articles, the average life obtained in their application is 13,000 hours. Using this as the MTBF the failure rate is 7.5%/1000 hours.



POWER VS. LIFE



DATE ISSUED: 12/1/63

REPORT NO.: 1

SUMMARY OF TEST RESULTS	*No. Tested*	*Total Tube Hours*	*No. Failed*	*Failure Rate in % Per 1000 Hours Confidence Factor 60%*	*90%*
Catastrophic Failures	106	104,653	0	< .88	< 2.2
Total Failures (Catastrophic & Electrical)	106	104,653	0	< .88	< 2.2

TEST DESCRIPTION:

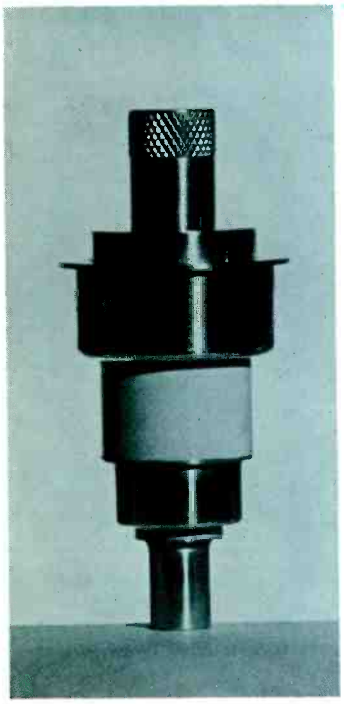
Per MIL-E-1/1429A (NAVY)
Group B — Ef = 6.0 Vac, Filament Standby; Time — 500 Hours
"At zero hours, establish the drive conditions necessary to obtain 2.0 amperes peak anode current with an anode voltage of 1000 Vdc and a bias voltage of —40 Vdc. The pulse width of the modulator shall be 2 μs (minimum) and the duty shall be 0.0025 maximum. With the drive level determined at zero hours check the anode current at the end of life. The maximum allowable drop in anode current is 25%."

APPLICATIONS:

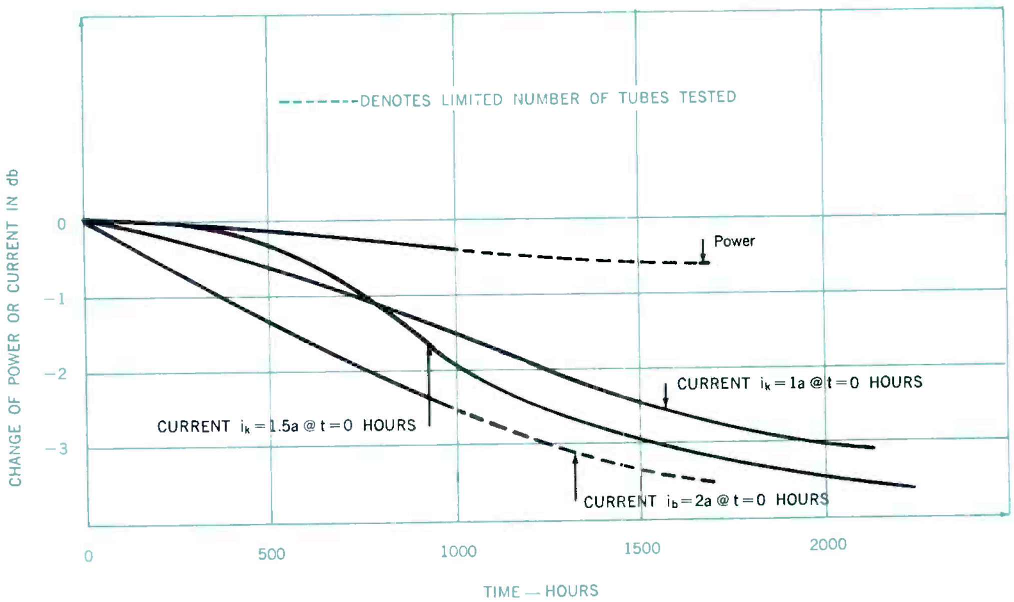
The ML-7815/3CPN10A5 is a high mu Planar Triode designed for use as a grid-pulsed or plate-pulsed oscillator, frequency multiplier or power amplifier in radio transmitting service from low frequency to 3000 mc.

REMARKS:

See Cathode Press Vol. 20, No. 4, 1963, "Evaluation of Negative Grid Tubes in Pulsed Applications for High Volumn Consumption in Phased Array Radar." P. 2. Claim 0 failures after total running time of 3700 hours per tube.



POWER AND CURRENT VS. LIFE



DATE ISSUED: 12/10/63 *REPORT NO.: 1*

SUMMARY OF TEST RESULTS	*No. Tested*	*Total Tube Hours*	*No. Failed*	*Failure Rate in % Per 1000 Hours Confidence Factor 60%*	*90%*
Catastrophic Failures	69	45,186	0	< 2.1	< 5.1
Total Failures (Catastrophic & Electrical)	69	45,186	0	< 2.1	< 5.1

TEST DESCRIPTION:

Per MIL-E-1/1470 (NAVY)

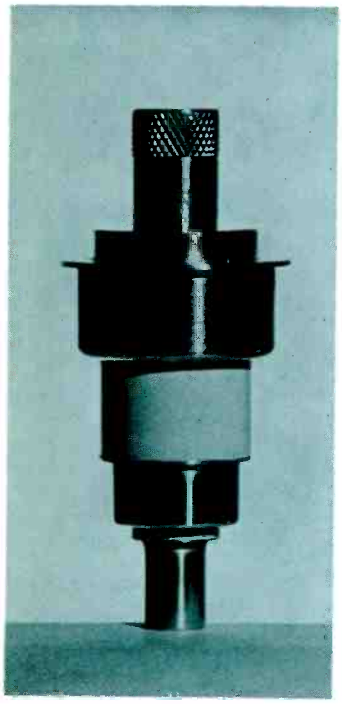
Group B

Filament Standby Ef = 6.3 Vac. Time — 500 Hours

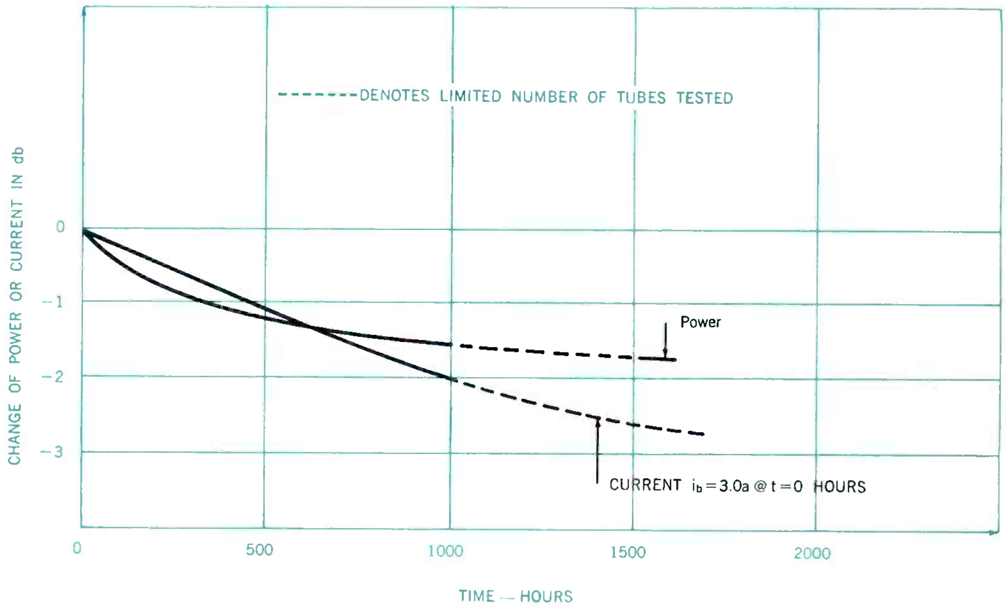
"At zero hours of life test establish the drive conditions necessary to obtain a peak plate current of 3a (minimum) with a plate voltage of 1000 Vdc and a bias of —40 Vdc. The pulse width of the modulator shall be 2 μs (minimum) and the duty shall be 0.0025 (maximum). With the drive level determined at zero hours, check the plate current at end of life. Maximum allowable drop in plate current shall be 25%."

APPLICATIONS:

The ML-7698 is a high-mu Planar Triode designed for use as a grid-pulsed or plate-pulsed oscillator, frequency multiplier or power amplifier in radio transmitting service from low-frequency to 3000 mc.



POWER AND CURRENT VS. LIFE



DATE ISSUED: 12/1/63

REPORT NO.: 1

SUMMARY OF TEST RESULTS	*No. Tested*	*Total Tube Hours*	*No. Failed*	*Failure Rate in % Per 1000 Hours Confidence Factor 60%*	*90%*
Catastrophic Failures	126	65,837	0	< 1.28	< 3.15
Total Failures (Catastrophic & Electrical)	126	65,837	1	< 2.75	< 5.08

TEST DESCRIPTION:

Per MIL-E-1/1055A

Group C

Time = 500 Hours

Pulsed Oscillation F = 3450 MC Minimum

e_{pg} = 3000 V; Rg/Ib = 2.5 madc; tpv = 1.0 usec ± 10%

trv = 0.1 usec, Maximum, tfr = 0.2 usec, Maximum;

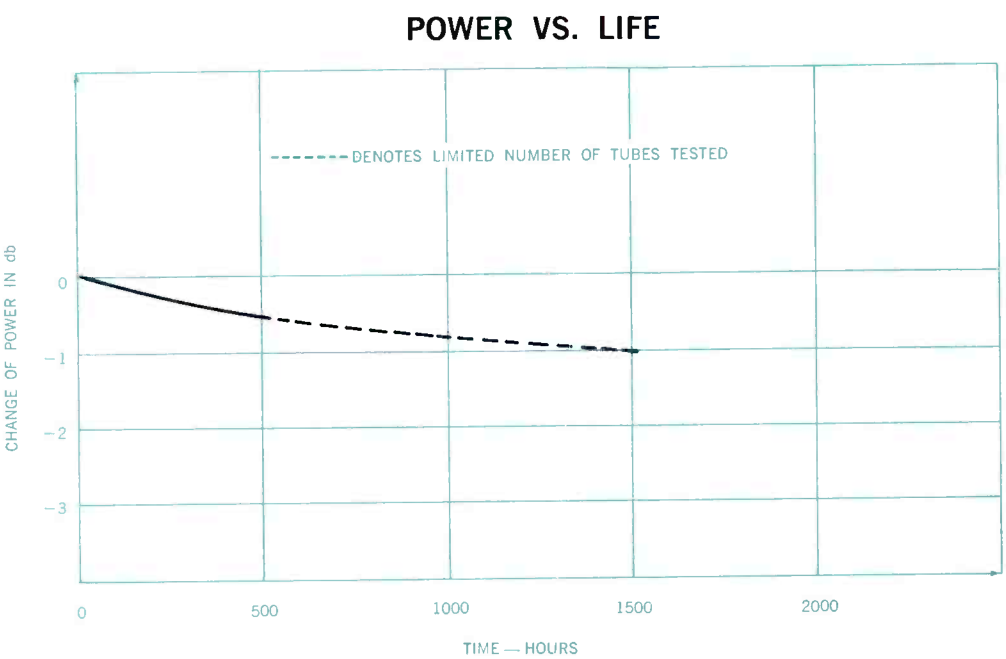
prΩ/Du = 0.001 ± 5%

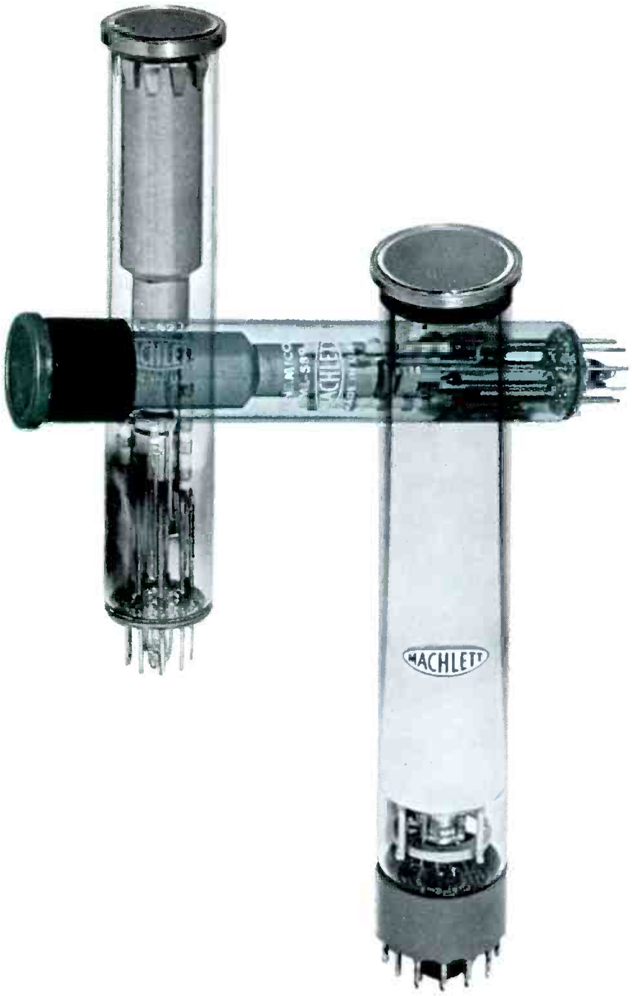
E_F = 6.0 V

ΔPo — 25% Maximum

APPLICATIONS:

The ML-6442 is a metal-ceramic envelope, medium-mu Triode of the Planar-Electrode type designed specifically for use as a plate-pulsed oscillator and amplifier at frequencies up to about 5000 mc. It can also be used as a cw oscillator, rf power amplifier or frequency multiplier at frequencies up to 2500 mc.





Machlett Special-Purpose Vidicons

The design, development and production of specialized, high-quality TV vidicon camera tubes is a unique capability of The Machlett Laboratories. Since entering the vidicon field with a broadcast vidicon that provided "live" quality to film transmission in mid-1958, Machlett has continued to advance the state of the art with a succession of new and difficult-to-produce vidicons. The current Machlett line, described on succeeding pages, consists of exclusive, special purpose, high quality tubes. Each of these tubes represents a technological breakthrough which was the culmination of extensive research and custom engineering.

In addition to exclusively Machlett development programs, the Company is continually engaged in sponsored development on special or custom vidicons for the military, private research institutions and others. Machlett, with its staff of specialists, continues to solicit sponsored development programs.

Among the special Machlett vidicons, currently used in slow-scan systems in satellite applications, is the ML-7351A. It is highly sensitive in the red region, and has lag characteristics that make this tube particularly adaptable to CCTV systems viewing radar scopes, and the like.

Two tubes in the line — the ML-S522B and the ML-2128G — have spectral response which peaks near the ultraviolet region. Applications of these tubes include TV display of ultraviolet microscope images of specimens which could not be viewed, or would be changed by exposure to visible light.

The incorporation of fiber-optics faceplates as an integral part of the ML-2128G and the ML-2128U vidicons has significantly advanced the capability of TV systems. With fiber optics, images can be transferred over short or long distances (in this case, short) with high sensitivity, efficiency, and resolution, while a lens system is restricted by its focal length.

The development of two x-ray sensitive camera tubes — termed DYNAMICONS* — combines instantaneous, enlarged x-ray image reproduction with protection for observing personnel. Performance of both static and in-motion medical and non-destructive radiographic examinations are notable advantages of these tubes.

The two-inch vidicon — represented by the ML-2058G and ML-2135G — was developed for applications which required a wider input field than was possible with the conventional ½″ x ⅜″ scanned area of the 1″ vidicon. The 2″ tubes provide for a full 1″ x 1″ raster.

On the following pages are the essential details and characteristics of the current Machlett vidicon line. Further inquiry on these tubes as to applications and capabilities, as well as special developmental requirements, is invited.

*Trade name registered by The Machlett Laboratories, Inc.

ML-7351/ ML-7351A
1″ High sensitivity at low light levels

The ML-7351 and 7351A are 1″ TV vidicon camera tubes designed for low light level applications with limited subject motion. The slow-scan and target storage characteristics of these tubes are particularly advantageous in CCTV systems, viewing radar display scopes. Resolution is normally about 500 TV lines (over 800 lines with elevated focusing potential). Sensitivity is extremely high; scenes with as little as 0.05 fc illumination on the faceplate can be registered. For average scenes, this corresponds to 2.5 fc illumination on a scene when using an f/2 lens. Spectral response peaks at 6000 Å (in red region), and is somewhat dependent on dark current. Signal decay rate is approximately half that of standard light-sensitive vidicons. The ML-7351 has a side tip protrusion; ML-7351A does not have side tip, which permits use of longer deflection yoke.

ML-2128G
1″ High contrast; fiber-optics input

The ML-2128G is a 1″ TV vidicon camera tube with a fiber-optics faceplate. This faceplate permits the tube to be directly coupled to cathode ray, storage or image intensifier tubes provided with fiber-optics output. Fiber-optics combinations for such purposes greatly increase light transmission capabilities, are lighter in weight and utilize less space than comparable optically coupled devices. Spectral response is S-18. Resolution is 600 TV lines. High contrast is enhanced by means of extra-mural absorbtion in the fiber optics.

ML-S522B
1″ Fast, near UV spectral response

The ML-S522B is a 1″ TV vidicon camera tube which is sensitive to near ultraviolet illumination. It is ideally suited for TV systems coupled to devices such as the ultraviolet microscope, which provides increased resolving power with the advantages of fluorescence. The S-522B spectral response peaks at 4000Å. When used with monochromatic radiation at this wavelength, the tube has a sensitivity of about 4.5 $\mu a/\mu w$. Resolution is normally 500 TV lines, but may be higher with elevated focusing potentials. Signal decay rate is approximately double that of standard light-sensitive vidicons.

ML-2128U
1″ Near UV; fiber optics input

The ML-2128U is a 1″ TV vidicon camera tube that has a fiber-optics faceplate. It is sensitive to near ultraviolet illumination, and is especially suited for TV coupling to cathode ray, storage or image intensifier tubes which are provided with fiber-optics output. Such fiber-optics combinations are usually smaller, lighter in weight and have greater light-transmission qualities than comparable lens coupled devices. Spectral response peaks at 4000 Å, which permits increased over-all sensitivity when used with devices having ultraviolet-emitting output screens. Resolution is approximately 500 TV lines; high contrast is obtained by means of extra-mural absorption in fiber optics.

ML-2058G
2″ High resolution; 1.4″ diagonal image

The ML-2058G is a 2″ TV vidicon camera tube which provides high-detail resolution. It may be used with conventional image orthicon magnetic deflection coils. Length is 12″. Features include: a 1″ x 1″ raster (1.4″ diagonal working area); a limiting resolution exceeding 2000 TV lines, 1100 TV lines at 50% amplitude modulation; S-18 spectral response. Transfer Characteristics and Aperture Response Curves follow "Typical Operating Conditions." Development of a 2″ tube with a near UV response is both practical and feasible.

ML-589
1″ X-ray sensitive; High contrast image

The ML-589 DYNAMICON is a 1″ TV camera tube which is sensitive to x-radiation incident on its faceplate. It provides high-contrast images with detail resolution down to .0005″, and penetrameter sensitivities to 2% when used with an adequate CCTV system and x-ray source. This tube makes possible static and in-motion non-destructive examinations of metal weldments, encapsulated components, and biological specimens. Magnifications to 50X easily obtainable. Resolution of 300 ASA phosphor bronze mesh and .0005″ dia. single tungsten wires (at faceplate) can be obtained without additional absorber in x-ray beam. Tube has a low-absorption beryllium faceplate.

ML-2135G
2″ X-ray sensitive; 1.4″ diagonal image

The ML-2135G DYNAMICON is a 2″ TV camera tube which is sensitive to x-radiation incident on its faceplate. This tube permits high-contrast images, brightness intensification, remote viewing and improved x-ray protection. It has a 1″ x 1″ raster (1.4″ diagonal working area). Resolution of 300 ASA phosphor bronze mesh and .0005″ dia. single tungsten wires (at faceplate) can be obtained without an additional absorber in the x-ray beam. This tube is ideally suited for static and in-motion non-destructive examinations of metal weldments, encapsulated components, and biological specimens, especially for applications that cannot be adequately scanned by 1″ ML-589.

GENERAL CHARACTERISTICS

	Units	ML-7351/ ML-7351A 1" High-Sensitivity
Heater, for Unipotential Cathode:		
Voltage (AC or DC)	V	6.3 ± 10%
Current	A	.6
Direct Interelectrode Capacitance, Signal Electrode to All Other Electrodes (Note 1)	pf	4.5
Spectral Response	—	See Curve
Photoconductive Layer:		
Aspect ratio of rectangular image	—	4 x 3
Maximum useful diagonal image	in.	.62
Orientation of quality rectangle	—	Note 2
Focusing Method	—	Magnetic
Deflection Method	—	Magnetic
Operating Position	—	Any
Overall Length	in.	6.25 ± .25
Greatest Diameter	in.	1.125 ± .010 (Note 4)
Bulb	—	T-8
Base, JEDEC No.	—	E8-11
Socket, equivalent to Cinch No.	—	54A18088
Weight, approximate	oz	2

FIBER-OPTICS CHARACTERISTICS

Fiber Diameter	microns	
Faceplate Thickness	in.	
Numerical Aperture, nominal	—	

Note 1 — This capacitance, which effectively is the output impedance of the vidicon, is increased when the tube is mounted in the deflecting-yoke and focusing-coil assembly. The resistive component of the output impedance is in the order of 100 megohms.

Note 2 — Proper orientation is obtained when the horizontal scan is essentially parallel to the plane passing through the tube axis and short index pin.

ML-2128G 1″ Fiber-Optics Input	**ML-S522B** 1″ Near-UV	**ML-2128U** 1″ Near-UV/ Fiber-Optics	**ML-2058G** 2″ High-Resolution	**ML-589** 1″ X-Ray Sensitive	**ML-2135G** 2″ X-Ray Sensitive
6.3 ± 10%	6.3 ± 10%	6.3 ± 10%	6.3 ± 10%	6.3 ± 10%	6.3 ± 10%
.6	.6	.6	.6	.6	.6
4.5	4.5	4.5	6.5	4.5	6.5
S-18	See Curve	See Curve	S-18	X-ray	X-ray
4 x 3	4 x 3	4 x 3	1 x 1	4 x 3	1 x 1
.62	.62	.62	1.4	.62	1.4
Note 2	Note 2	Note 2	Note 3	Note 2	Note 3
Magnetic	Magnetic	Magnetic	Magnetic	Magnetic	Magnetic
Magnetic	Magnetic	Magnetic	Magnetic	Magnetic	Magnetic
Any	Any	Any	Any	Face up to horizontal	Any
6.25 ± .25	6.25 ± .25	6.25 ± .25	12.0 ± .25	6.25 ± .25	12.0 ± .25
1.125 ± .010	1.125 ± .010	1.125 ± .010	2.25 ± .010	1.125 ± .015	2.25 ± .010
T-8	T-8	T-8	—	—	—
E8-11	E8-11	E8-11	B14-45	E8-11	B14-45
54A18088	54A18088	54A18088	—	54A18088	—
2	2	2	10	2	10
7		7			
.09		.09			
.84		.84			

Note 3 — Proper orientation is obtained when the horizontal scan is essentially parallel to the plane passing through the tube axis and base key.

Note 4 — ML-7351 has a side tip projecting beyond maximum diameter.

MAXIMUM RATINGS

	Units	ML-7351/ ML-7351A 1″ High-Sensitivity
Absolute Values for a scanned area as noted	in.	½ x ⅜
Signal-Electrode Voltage	Vdc	75
Grid No. 4 and Grid No. 3 Voltage	Vdc	1000
Grid No. 2 Voltage	Vdc	500
Grid No. 1 Voltage:		
Negative bias value	Vdc	125
Positive bias value	V	0
Peak Heater-Cathode Voltage:		
Heater negative with respect to cathode	v	125
Heater positive with respect to cathode	v	10
Dark Current	uAdc	.1
Peak Target Current	ua	.55
Faceplate Temperature	°C	71
Faceplate Illumination	fc	100

TYPICAL OPERATING CONDITIONS

Signal-Electrode Voltage	Vdc	10 to 25
Grid No. 4 (Decelerator) and Grid No. 3 (Beam-Focus Electrode) Voltage (Note 7)	Vdc	250 to 300
Grid No. 2 (Accelerator) Voltage	Vdc	300
Grid No. 1 Voltage for Picture Cutoff (Note 8)	Vdc	—45 to —100
Minimum Peak-to-Peak Blanking Voltage:		
When applied to Grid No. 1	v	40
When applied to Cathode	v	10
Faceplate Illumination, highlight	fc	.3 to .7
Faceplate Temperature	°C	30 to 35
Dark Current	uAdc	.02
Target Current, highlight (Note 9)	uA	.32 to .42
Average Gamma for Transfer Characteristics	—	.65
For signal output current as given	uA	.02 to .2
Visual equivalent Signal-to-Noise Ratio, approx. (Note 10)		300:1
Field Strength at Center of Focusing Coil, approx.	gauss	40
Field Strength of Adjustable Alignment Coil	gauss	0 to 4

Note 5 — The maximum signal-electrode voltage is determined by the secondary emission first cross-over potential of the photoconductive layer. With a conventional deflection field rate of 60 cps, the cross-over potential will be reached, under no-radiation conditions, at a signal electrode voltage of between 35 and 50 volts. If the tube is operated above the first cross-over potential, the photoconductive surface will be stabilized by the G4 electrode. The potential across the photoconductive layer will then be the difference between the potentials applied to G4 and the signal-electrode.

If operated above the first cross-over potential during early life, this tube is very susceptible to picture and raster burns due to the high potential gradient across the layer. Although this effect becomes less apparent with increased operating hours, the manufacturer deems it advisable to limit the signal-electrode potential to a few volts below the cross-over point in order to prevent picture deterioration. The maximum signal-electrode potential is therefore given for each tube delivered.

With the beam off, the cross-over will be reached with a somewhat lower signal-electrode potential, as a result of the extended photoconductive storage time. It is important, therefore, to turn the beam on before increasing the signal-electrode potential above zero.

ML-2128G 1" Fiber-Optics Input	ML-S522B 1" Near-UV	ML-2128U 1" Near-UV/ Fiber-Optics	ML-2058G 2" High-Resolution	ML-589 1" X-Ray Sensitive	ML-2135G 2" X-Ray Sensitive
½ x ⅜	½ x ⅜	½ x ⅜	1 x 1	½ x ⅜	1 x 1
75	40	40	75	Note 5	Note 5
1000	1000	1000	3500	1000	3500
500	500	500	350	500	350
125	125	125	125	125	125
0	0	0	0	0	0
125	125	125	125	125	125
10	10	10	10	10	10
.25	.02	.02	1.0	Note 6	Note 6
.55	.55	.55	2.0	.40	1.4
71	45	45	60	45	45
1000	—	—	1000	—	—
15 to 35	10 to 25	10 to 25	25 to 60	10 to 30	10 to 30
250 to 300	250 to 300	250 to 300	2900 to 3100	250 to 300	2900 to 3100
300	300	300	300	300	300
—45 to —100	—45 to —100	—45 to —100	—45 to —100	—45 to —100	—45 to —100
75	40	40	75	75	75
20	10	10	20	20	20
15	—	—	15	—	—
30 to 35	30 to 35	30 to 35	30 to 35	20 to 30	20 to 30
.02	.005	.005	.08	(Note 6)	(Note 6)
.32 to .42	.2 to .4	.2 to .4	1.2 to 1.6	—	—
.65	—	—	.65	—	—
.02 to .2	—	—	.08 to .8	—	—
300:1	300:1	300:1	300:1	300:1	300:1
40	40	40	60	40	60
0 to 4	0 to 4	0 to 4	0 to 3	0 to 4	0 to 3

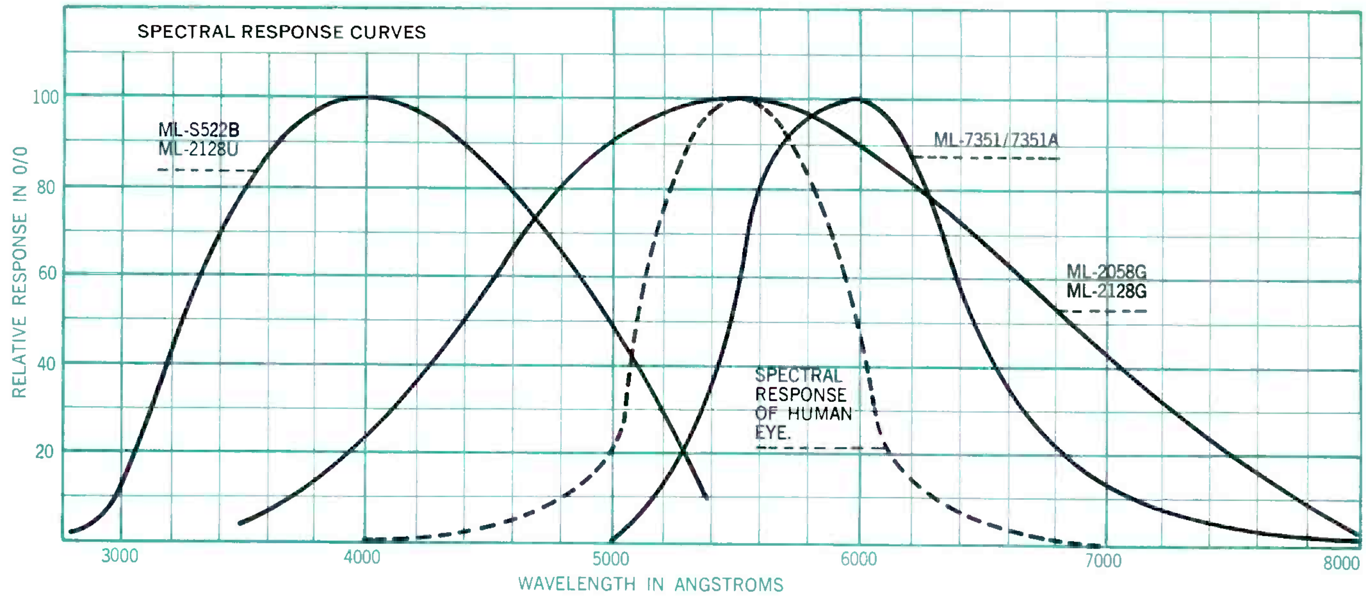
Note 6 — The characteristics of the photoconductive surface are such that the operating dark current is extremely small compared to that obtained with conventional light-sensing vidicons. It is somewhat difficult to measure due to the presence of leakage currents, and it is not therefore considered a useful operating parameter.

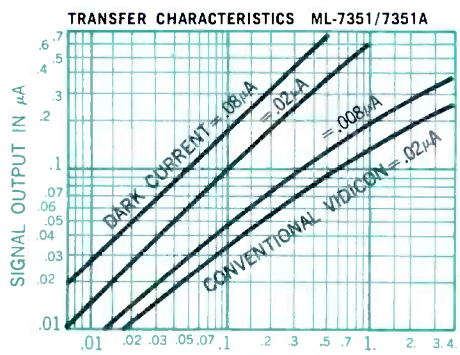
Note 7 — Definition, focus uniformity and picture quality decrease with decreasing Grid No. 3 and Grid No. 4 voltage. In general, Grid No. 3 and Grid No. 4 should not be operated below the lower value shown.

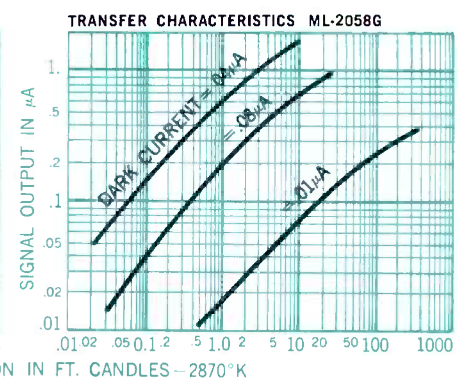
Note 8 — With no blanking voltage on Grid No. 1.

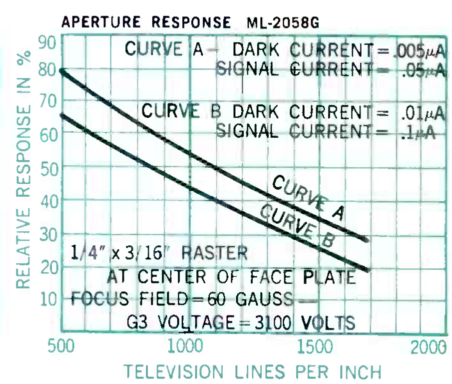
Note 9 — Video amplifiers must be designed properly to handle target currents of this magnitude to avoid amplifier overload or picture distortion.

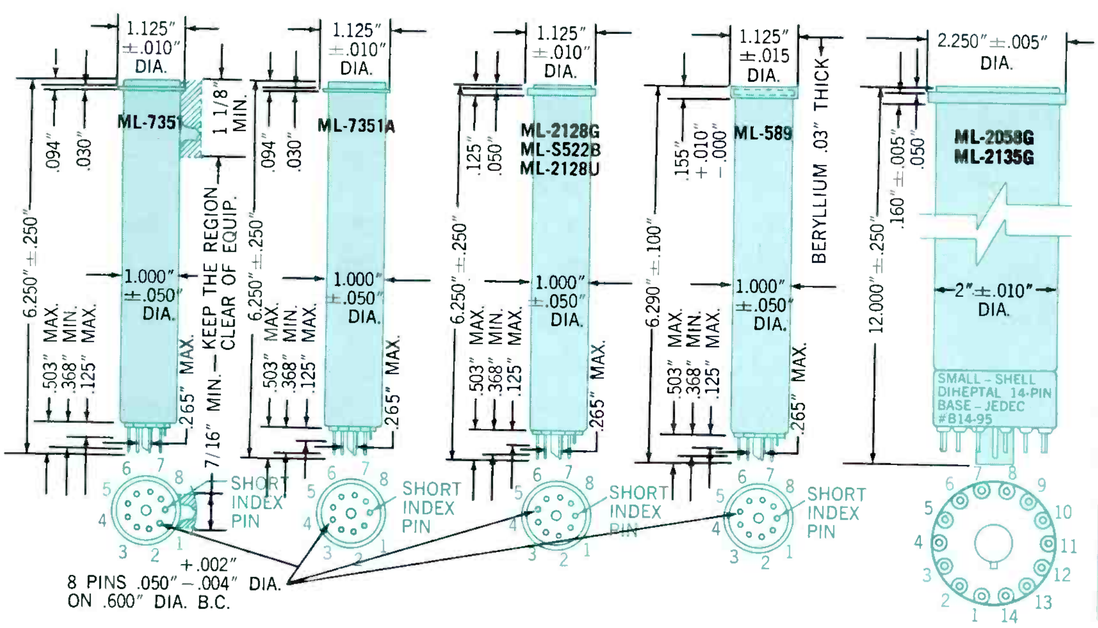
Note 10 — Measured with high-gain, low noise, cascode-input-type amplifier having bandwidth of 5 megacycles.











PIN CONNECTIONS FOR 1" TUBE	
PIN NO.	ELEMENT
1 & 8	HEATER
2	GRID NO. 1
3 & 4	INTERNAL CONNECTIONS—DO NOT USE
5	GRID NO. 2
6	GRID NO. 3 & GRID NO. 4
7	CATHODE
FLANGE	SIGNAL ELECTRODE
INDEX PIN	INTERNAL CONNECTION—DO NOT USE
2" TUBE	
2	GRID NO. 4
3	GRID NO. 3
4	INTERNAL CONNECTION—DO NOT USE
10	GRID NO. 2
13	CATHODE
1 & 14	HEATER
5 thru 12	GRID NO. 1

(Continued fron Page 15)

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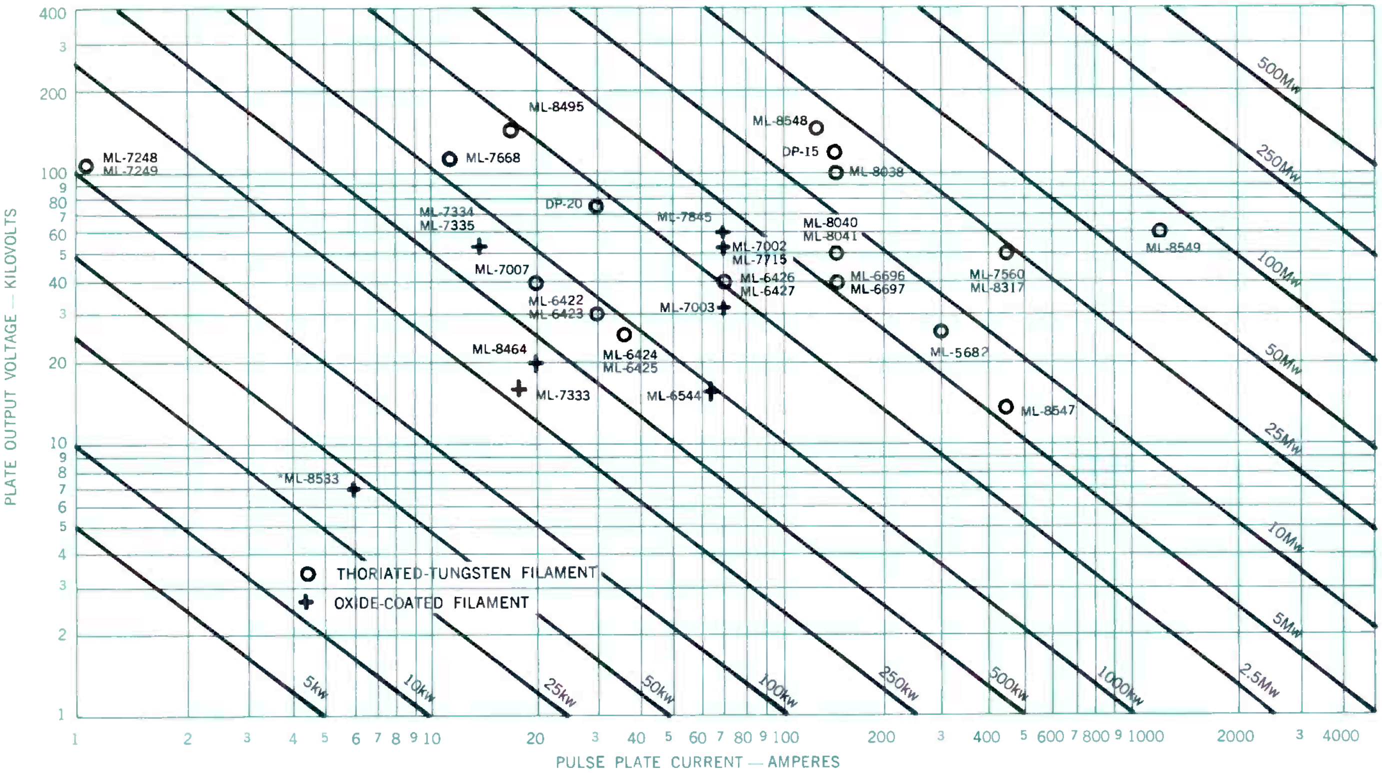
Appendix I

Switching Power of Machlett Pulse Tubes

Switching power of the current line of Machlett pulse tubes is indicated below. Each tube will deliver output current and voltage approximately up to values indicated by either an 0 or a +.

Lines of constant switching power through these coordinates show the range of current and voltage possible by the use of an output pulse transformer.



*UHF TRIODE. For data on other tubes of this type, Consult MACHLETT Engineering Department

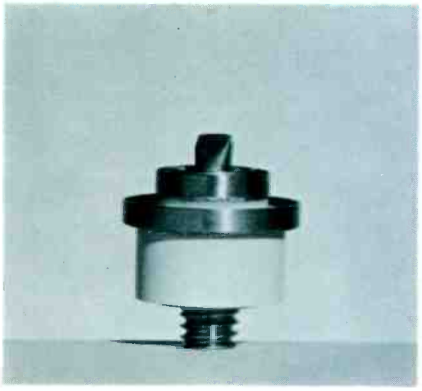
New Machlett Developments

Machlett announces a new line of miniature ruggedized, high-mu planar triodes illustrated below, ACTUAL SIZE. Performance of this miniature line is identical to that of the larger, conventional planar tubes.

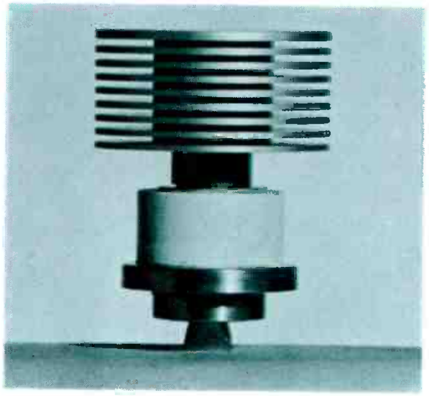
MAXIMUM RATINGS

	Units
Pulse Duration	usec
Duty Factor	%
Amplification Factor	—
DC Plate Voltage	kVdc
Peak Plate Voltage	kV
Peak Plate Pulse Supply Voltage	kV
DC Grid Voltage	Vdc
Instantaneous Peak Grid-Cathode Voltage	
Grid Negative to Cathode	v
Grid Positive to Cathode	v
Average Plate Current	mAdc
DC Plate Current	mAdc
Peak Plate Current from Pulse Supply	a
Peak Plate Current from DC Supply	a
Transconductance	mmhos
Average Grid Current	mAdc
Average Plate Dissipation	
Forced-Air or Heat-Sink Cooling	W
Conduction and Convection Cooling	W
Average Grid Dissipation	W

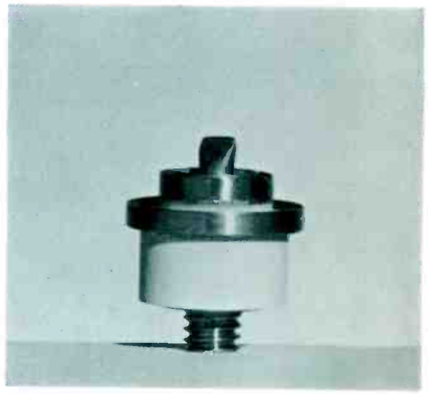
ML-8534



ML-8535



ML-8536



ML-8534 and ML-8535

For grid, plate-pulsed, or cw operation; frequency multipliers, oscillators, or amplifiers to 3 Gc. Both tubes employ **high current capability, phormat cathode, frequency stable anode;** and provide low interelectrode capacitance, and high transconductance.

ML-8536 and ML-8537

For grid, plate-pulsed, or cw operation; frequency multipliers, oscillators, or amplifiers to 3 Gc. Both tubes employ the **phormat cathode, frequency stable anode,** and provide low interelectrode capacitance and high transconductance.

ML-8538 and ML-8539

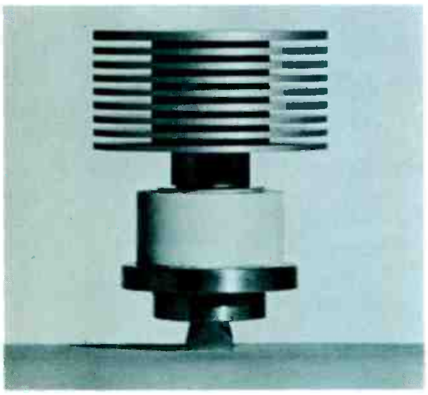
For use as **pulse modulators,** pulse amplifiers, grid-pulsed oscillators, or amplifiers and switch tubes. Frequency to 3 Gc. Tubes have **high current capability, and phormat cathode.**

• • •

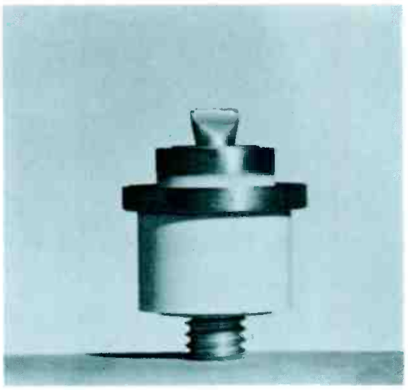
Switch tube to 30 kw max. at 0.0033 d

ML-8534/ML-8535 Pulsed UHF Oscillator & Amplifier: Grid-Pulsed	Plate-Pulsed	CW	ML-8536/ML-8537 Pulsed UHF Oscillator & Amplifier: Grid-Pulsed	Plate-Pulsed	CW	ML-8538/ML-8539 Pulse Modulator or Pulse Amplifier	Grid-Pulsed UHF Oscillator & Amplifier
6	6	—	6	6	—	6	6
.33	.33	—	.33	.33	—	.33	.33
80	80	80	80	80	80	90	135
2.5	—	2.5	2.5	—	2.5	8	7.5
—	—	—	—	—	—	10	—
—	3.5	—	—	3.5	—	—	—
−150	−150	−150	−150	−150	−150	−150	−150
−750	−750	−400	−750	−750	−400	−750	−750
+250	+250	+ 30	+250	+250	+ 30	+250	+250
16	16	—	10	10	—	—	16
—	—	150	—	—	100	150	—
—	5	—	—	3	—	5	—
5	—	—	3	—	—	—	5
—	—	30	—	—	25	—	30
6	6	45	5	5	45	—	6
33	58	100	20	35	100	100	100
10	10	10	10	10	10	10	10
1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

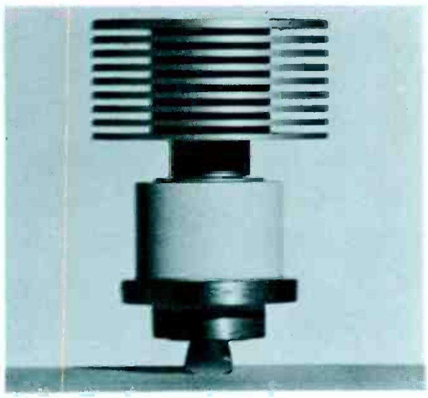
ML-8537



ML-8538



ML-8539



New Machlett Developments

ML-8464

Ruggedized shielded-grid triode for pulse generation to 2 Mw

Designed for operation while subjected to moderately high acceleration forces and is suitable for mobile radar applications. Delivers 400 kW pulse power output with less than 2 kW pulse driving power. Cathode is unipotential, oxide-coated; anode is liquid cooled.

Maximum Ratings, Pulse Modulator or Pulse Amplifier

DC Plate Voltage	25 kV
Pulse Cathode Current	25 a
Plate Dissipation	1.5 kW

Typical Operation

DC Plate Voltage	23 kV
DC Grid Voltage	—250 V
Pulse Positive Grid Voltage	1.1 kV
Pulse Plate Current	20 a
Pulse Grid Current	1.4 a
Pulse Driving Power	2 kW
Pulse Power Output	400 kW
Plate Output Voltage	20 kW

ML-8547

General-purpose, low-mu triode capable of 6 Mw pulse modulator service

ML-8547 is capable of switching 6 Mw in a pulsed modulator at relatively long pulse duration and high duty factor. Incorporates integral water jacket, sturdy coaxial grid and cathode mounting structures, and thoriated tungsten filament; provides low - inductance, high - dissipation, rf terminals.

Maximum Ratings, Pulse Modulator or Pulse Amplifier

DC Plate Voltage	16 kV
Pulse Cathode Current	550 a
Plate Dissipation	175 kW

Typical Operation

DC Plate Voltage	15 kV
DC Grid Voltage	—2000 V
Pulse Positive Grid Voltage	1.3 kV
Pulse Plate Current	250 a
Pulse Grid Current	70 a
Pulse Driving Power	235 kW
Pulse Power Output	3.5 Mw
Plate Output Voltage	14 kV

ML-2080G

9″ Light-Sensitive image intensifier with fiber-optics output

Primarily designed for medical applications. Has light sensitive photocathode with fiber optics output.

Input Diameter	Approx. 8.6″
Output Diameter	Approx. 1.0″
Photocathode	S = 20
Output Phosphor (Optional) (Other phosphor and optical flat glass on request)	P = 20
Brightness Gain (incl. minification)	10,000X
Photocathode Sensitivity	100 ua/L (min.)
Resolution at Photocathode	60 lp/in
Resolution of Output	500 lp/in
Fiber Optics Diameter	7 micron fibers (extramural absorption)
Operating Voltage (Nominal)	24 kV

About the Authors

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Dr. Doolittle is Manager of Technology of The Machlett Laboratories, Inc., and has been responsible for the development of UHF and high power triodes and tetrodes as well as research on cathodes and allied subjects. He is also responsible for over-all scientific work of the engineering staff with particular emphasis on new products and processes. Dr. Doolittle is a fellow of the American Physical Society, and a Member of IEEE and the Electrochemical Society.

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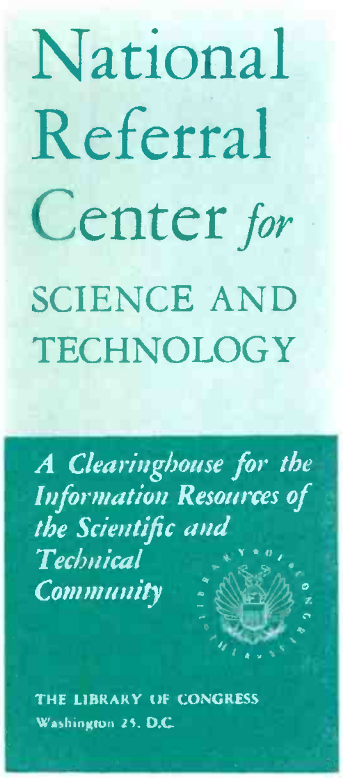

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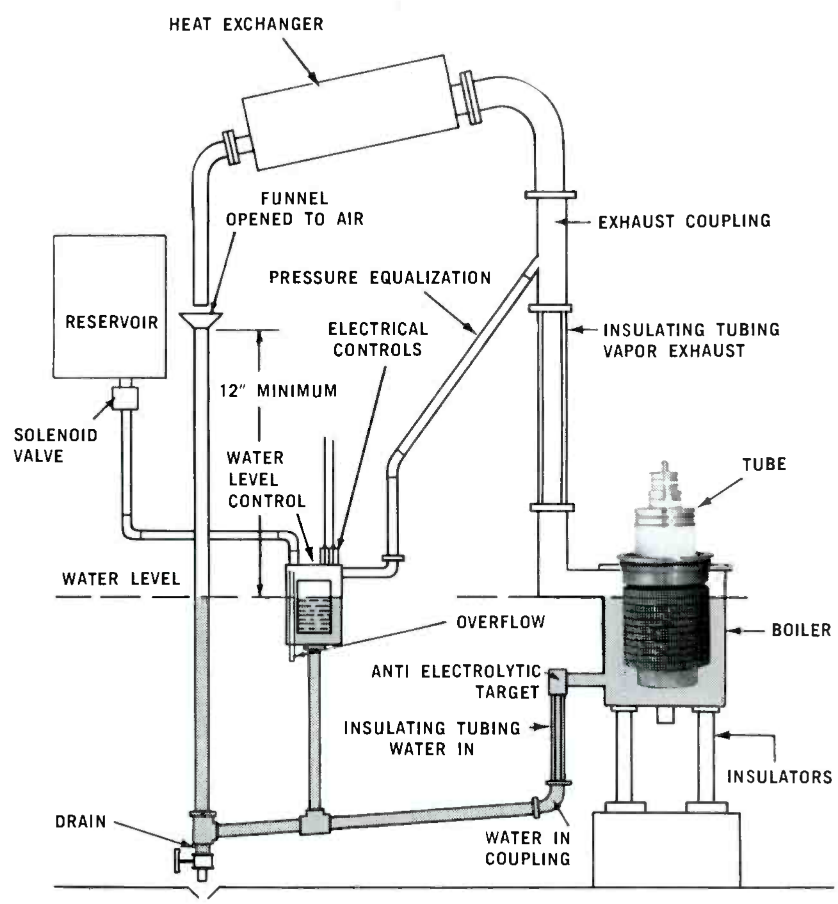

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SYSTEM	TYPICAL APPLICATION
Vapor-Up (shown above)	General Broadcast (HF)
Vapor-Down	General & SSB Communications (HF)
Boiler Condenser	Industrial
Integrated	Special Service. Particularly suited to VHF.

System advantages include: 200-300% greater anode dissipation as compared to forced-air cooling; 10-20% greater anode dissipation over conventional water cooling; extremely large overload protection for anode; stable, quiet cooling; low water consumption; low operating costs.

Each of the above four systems is highly adaptable to a wide range of applications. Consider the advantages of each system—outlined in "Vapor Cooling," obtained by writing to The Machlett Laboratories, Inc., Springdale, Conn., an affiliate of Raytheon Company.

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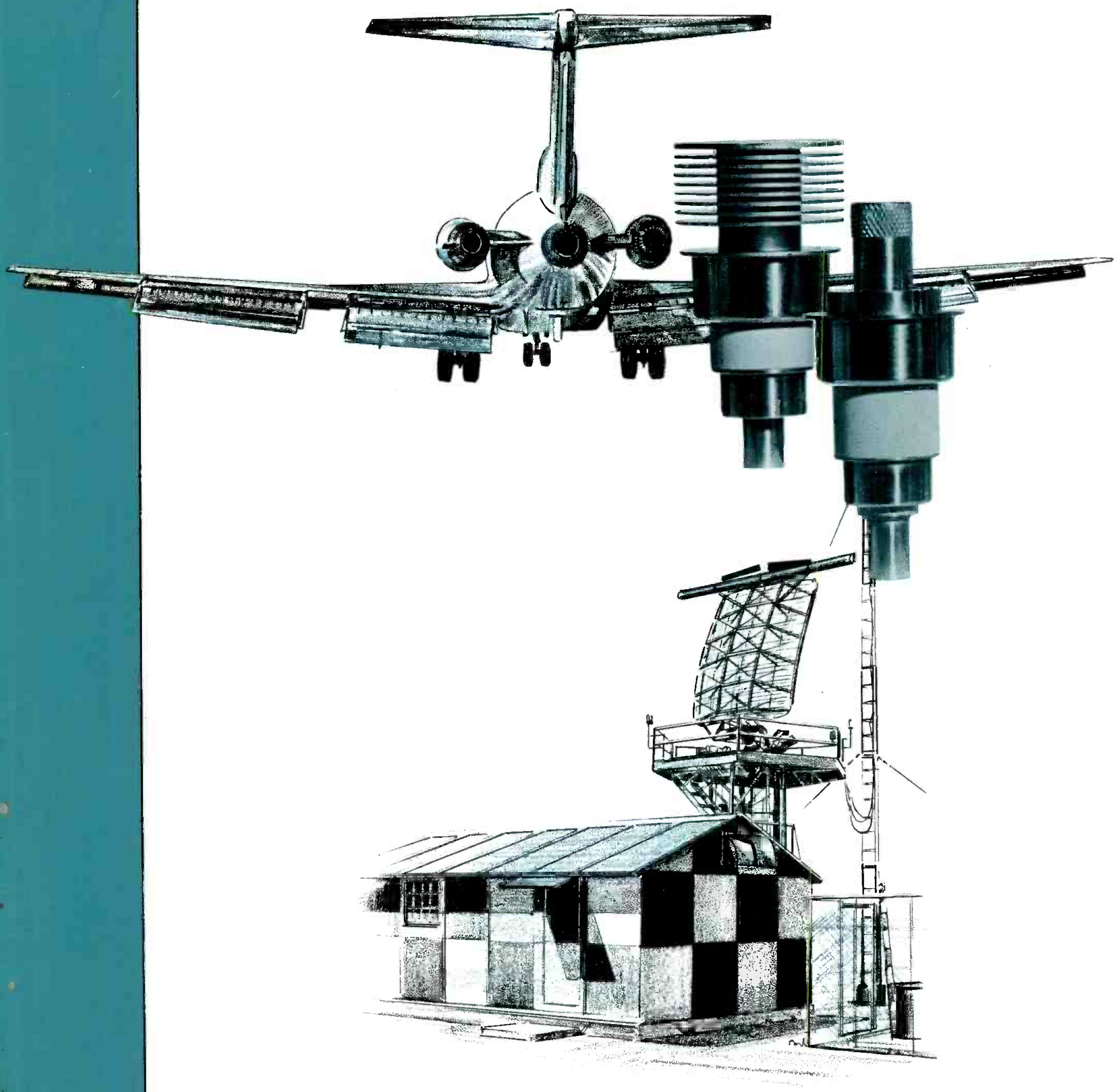
MACHLETT CATHODE PRESS



VOL. 21 • NO. 2 • 1964

CATHODE PRESS

Vol. 21, No. 2, 1964

Editor, *Richard N. Rose*

Art Director, *Edward J. Bulger*

IN THIS ISSUE

Cover:

Machlett planar triodes serve the nation's commercial airlines for air traffic control in DME and Transponder equipment.

Product Lines represented in this issue:

Small Power Tubes

Large Power Tubes

JULY 1964

PRINTED IN U.S.A.

MACHLETT

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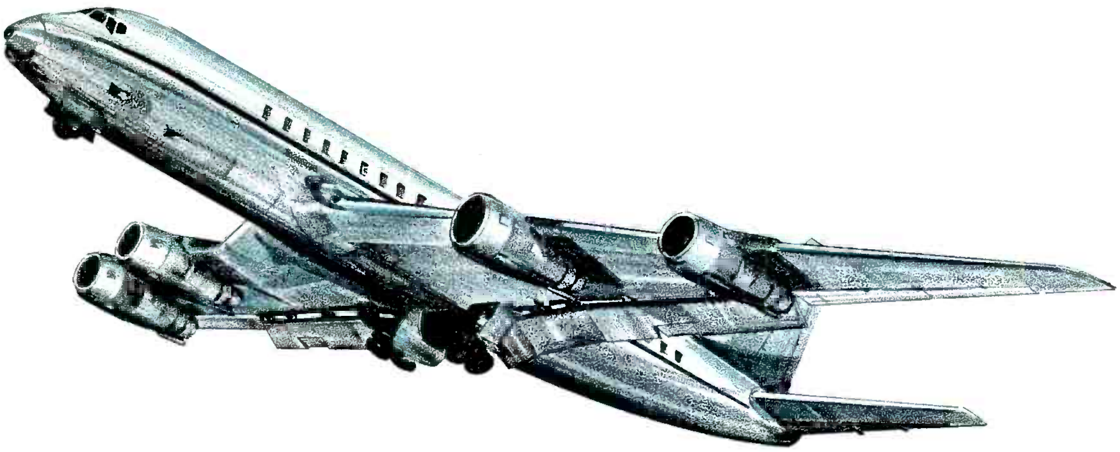


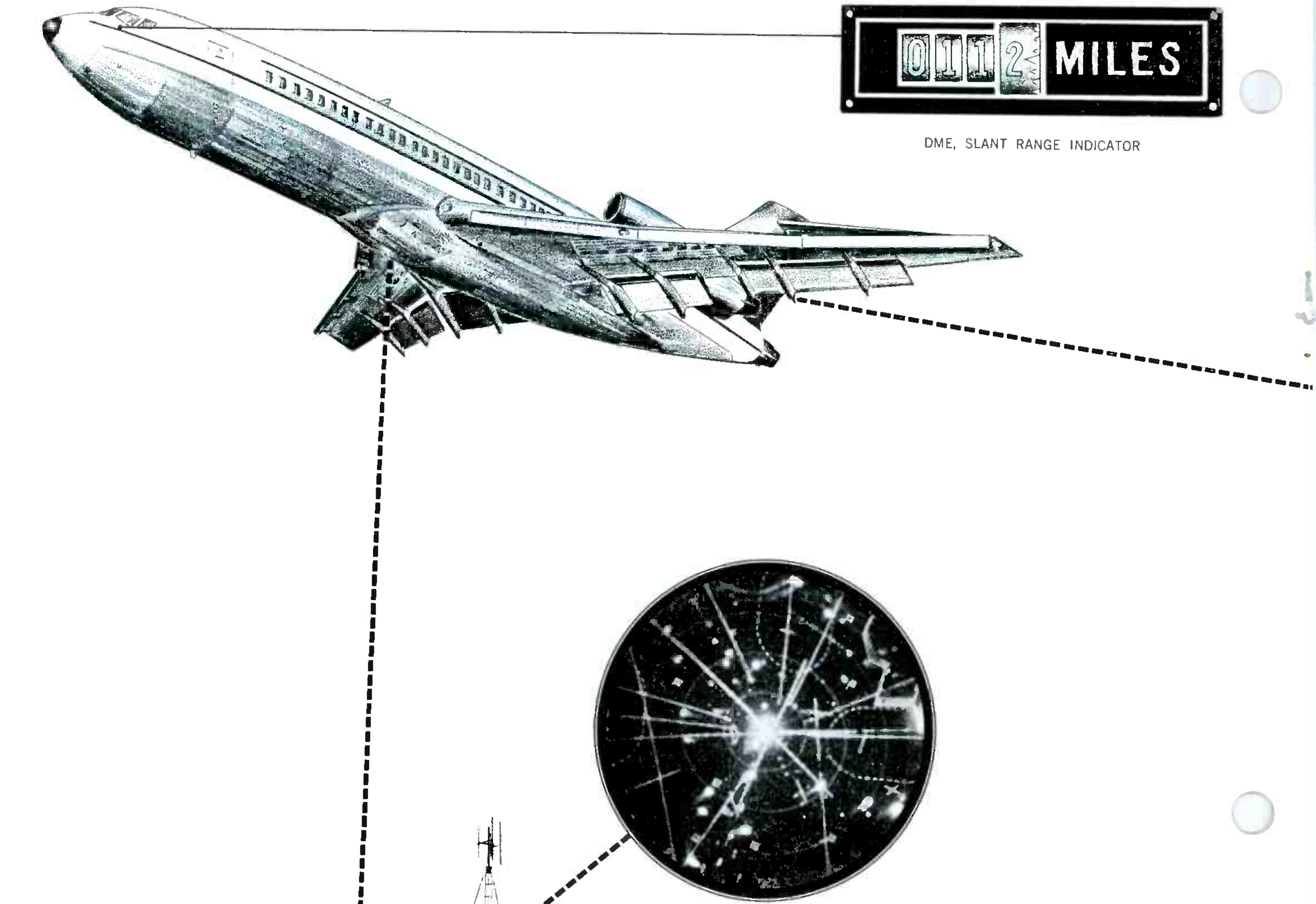
Introduction

In this and in the following issue Machlett Laboratories' position in the field of commercial aviation is reviewed by CATHODE PRESS. At a time when the use of solid state devices has become nearly universal in new airborne electronics equipment, and the use of electron tubes has diminished accordingly, the Machlett planar triode continues to maintain — even increase — the extent of its application. Today all airlines flying 4 engine equipment use the DME and Beacon Transponder. In each of these units one or more planar triodes is employed.

Machlett planar triodes (including the ML-7855, ML-7815 and ML-6442) are used by the great majority of carriers as the preferred tube type. This is so because the equipment manufacturers, as described in this issue, have found significant advantage in the Machlett offering.

The Machlett contribution lies not only in the reliability of its planar triode but in the new level of performance it has made possible. In the areas of high voltage stability, grid pulsing, frequency stability, cathode activity and tube life, Machlett tubes have demonstrated superiority.

CATHODE PRESS, Volume 21, No. 2, describes DME and transponder development as seen by the manufacturer. Volume 21, No. 3 will describe the use made of these important navigation aids by several major airlines.



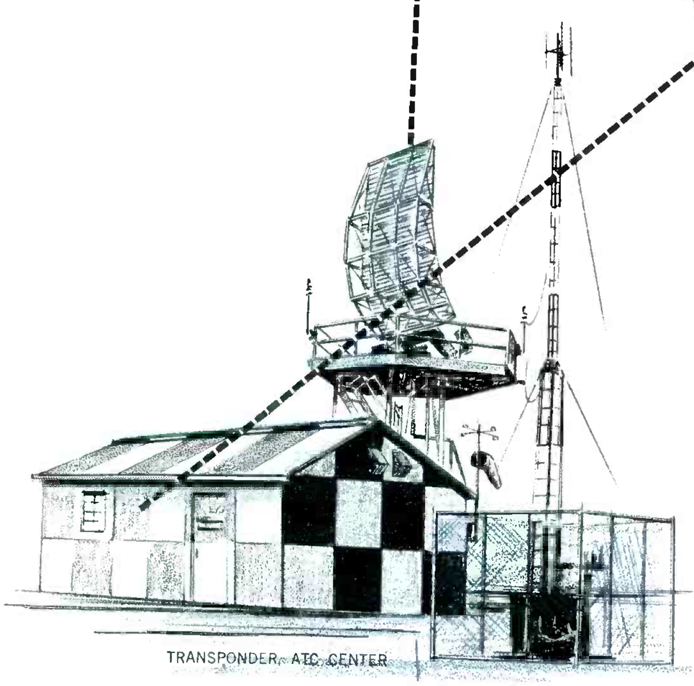


Figure 1 — Better Air Service with Modern Electronic Aids.

As late as World War II, there was little consideration given to the pilot and aircraft once they were airborne. Today, however, the crowding of the airways presents a problem and minutes are precious in handling the high volume of today's air traffic. Controller and pilot must function in unison, to prevent emergency situations in air corridors and landing patterns. Close control of aircraft from air and ground is necessary. It must be positive. It must be constant.

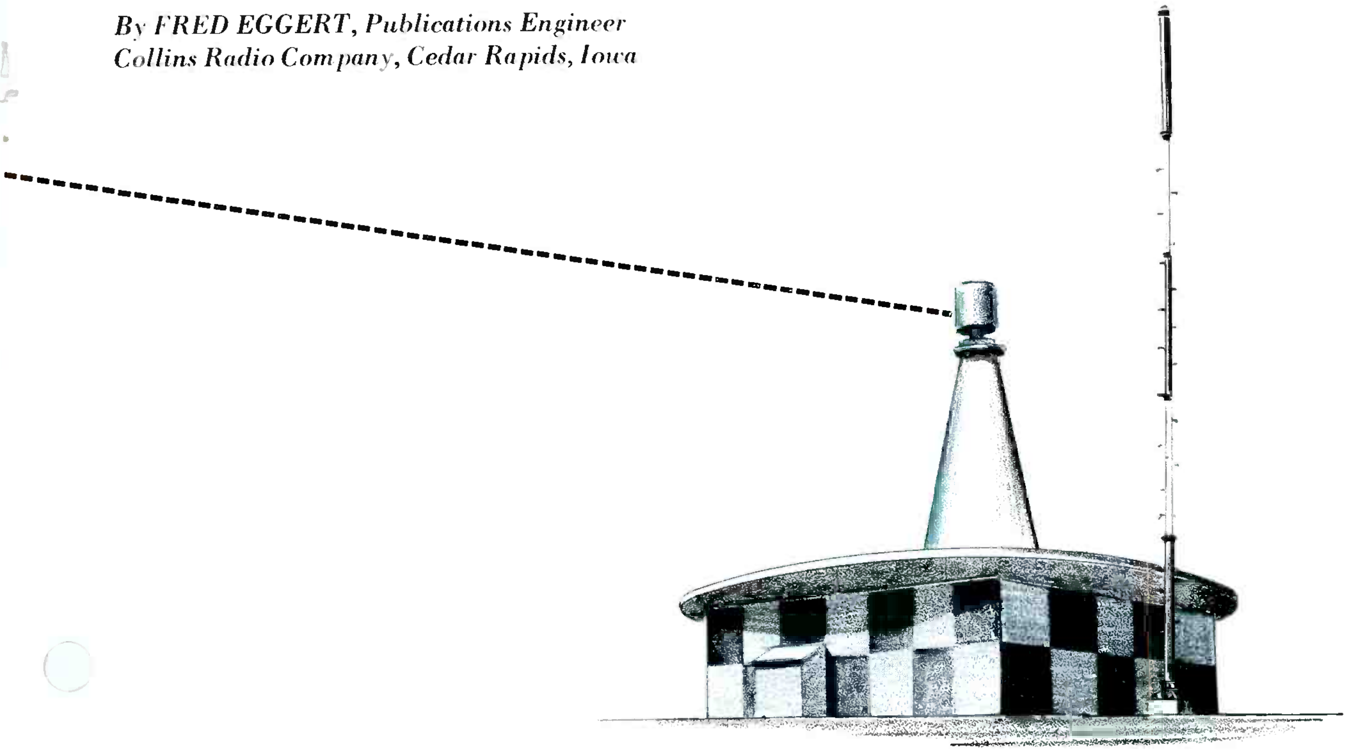
The Collins 621A-3 ATC Transponder and the 860E-2 DME (distance measuring equipment) extend the "controlability" of the pilot and the air traffic controller in good and (particularly) bad weather. They provide constant information of aircraft position and movements within a given sector. This knowledge, given to both pilot and ground controller, greatly reduces the possibility of an air tragedy and increases the serviceability of an airline.

ATC Transponder for Controller

Transponders are used for establishing the azimuth and distance of an aircraft from an ATC center. This is done by

Positive Control from Air and Ground

By FRED EGGERT, Publications Engineer
Collins Radio Company, Cedar Rapids, Iowa



VORTAC STATION

transmitting a coded interrogation from the ground station. The ATC Transponder (Figure 2) equipped aircraft receives this interrogation and decodes it. That is, it determines that it is in fact an interrogation to a transponder. The ATC Transponder codes a reply to the interrogation which is then transmitted to the ground station. An active reply rather than an echo is used to eliminate problems with precipitation, clouds, and ground clutter and to extend radar range. The ground station decodes and displays the reply on a cathode ray tube screen. The face of this tube is overlaid with a map to show the location of the aircraft with respect to airways, navaids, and holding areas. Coding of a reply signal is used in ATC to identify particular operating conditions of aircraft. The codes are displayed on a digital readout, which indicates whether the aircraft is climbing, flying at a particular altitude, or descending.

An air traffic controller can follow the progression of aircraft through a given sector, using the cathode ray tube representation. With a glance, he can determine which aircraft are in the area and their relative positions. And, using voice communications, the ground controller can direct or position the aircraft within the sector. Aircraft not equipped with a transponder are located using an echo-reply system and are integrated with those transponder equipped aircraft on the cathode ray tube screen. This gives the ground controller a complete air picture of all the aircraft in his sector.

Because transponder-equipped aircraft have the capability to provide the ATC controller with a continuous, positive indication of their position, it is possible for them to obtain clearances, which, if requested by non-transponder aircraft, would be either delayed or denied.

In planning flights, for example, it is often advantageous to go direct rather than to follow a series of airways which dog leg back and forth. Under IFR (instrument flight rules) conditions where there is extensive traffic, controllers are reluctant to grant direct clearances to non-transponder aircraft because of difficulty involved in providing separation of aircraft paralleling and crossing airways and going as long as 30 or 40 minutes between positive fixes.

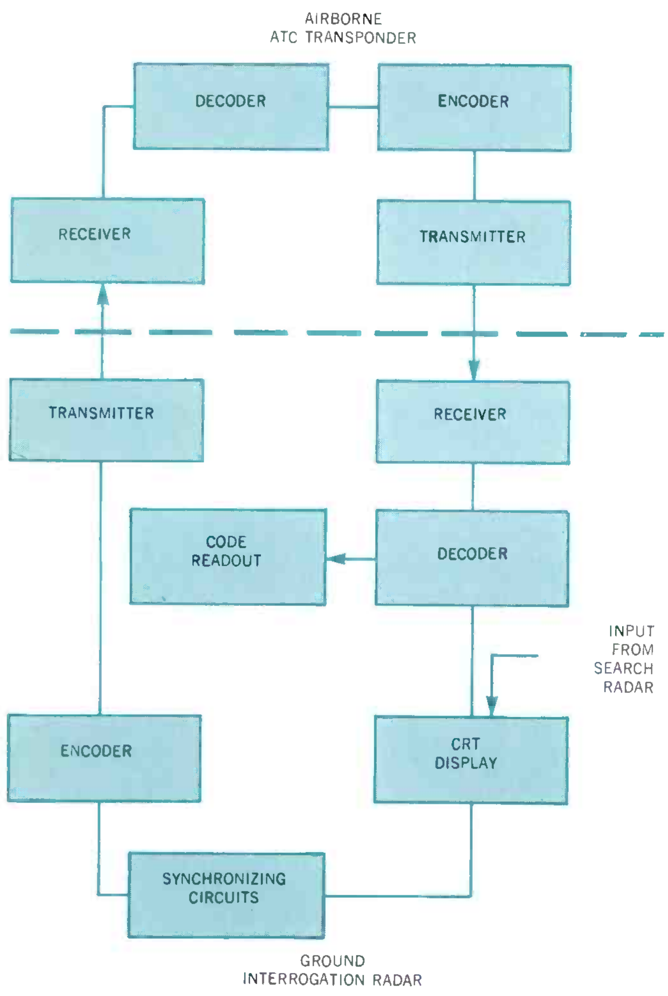
A transponder-equipped aircraft, however, because it is continuously fixed on the controller's scope, can be easily integrated with the airway traffic in the area. As a result, transponder equipped aircraft generally obtain clearances more quickly and experience fewer changes of flight plan and delays enroute.

In high density areas aircraft not equipped with a transponder are required to report over a definite fix and to make identifying turns as prescribed by the controller so that they can be positively identified. Only then can they be worked into the approach pattern. If, because of precipitation or ground clutter, the controller loses the target for any length of time, it may be necessary for the aircraft to once again be identified by executing a series of turns.

The transponder equipped aircraft, by way of contrast, is positively identified as soon as it appears on the approach controller's scope and is often vectored directly into the approach pattern, thereby saving a considerable amount of time.

If a situation should occur, either enroute or in a terminal area, that would require an immediate descent and landing, the transponder equipped aircraft can be quickly cleared and vectored to the nearest suitable field. Even if all VHF communications are lost, with an aircraft in distress, the transponder permits it to be quickly identified by transmitting the emergency pulse code. The other aircraft in the area could then be vectored so as not to conflict with the distressed aircraft.

Figure 2 — ATC Transponder System, Block Diagram.



The 621A-3 ATC Transponder

In addition to all of the attributes noted for transponders, in general, the Collins Radio Company 621A-3 ATC Transponder incorporates several new features. Completely solid state except for the transmitter tube, the 621A-3 incorporates both two and three pulse sidelobe suppression, an expanded reply code system of 4096 combinations, and all the circuits required for automatic altitude reporting. Space has also been reserved for the addition of such other functions, such as automatic selective reply on all modes, that may be required in the future. Also, a self-test feature is available which can be operated by a switch on the front panel of the radio and remotely by a switch on the control panel. This provision can be used to interrogate the transponder and check the reply to assure that the transponder is operating properly. The circuit gives a visual and aural indication of the transponder operation. This self-test check extends from the input of the receiver to the output of the transmitter. Receiver sensitivity, decoder performance, and transmitter power output can be checked on the ground or in flight using this feature.

The three-pulse sidelobe suppression system provides for an interrogation containing three pulses. The secondary surveillance radar (SSR) station transmits 0.8 microsecond wide pulse pair interrogations (P1 and P3) from the directional rotating antenna. Pulse spacing between P1 and P3 is determined by the mode of operation. Two microseconds after the initial interrogation pulse (P1) is transmitted, the

Figure 3 — ATC Transponder, Dust Cover Removed.

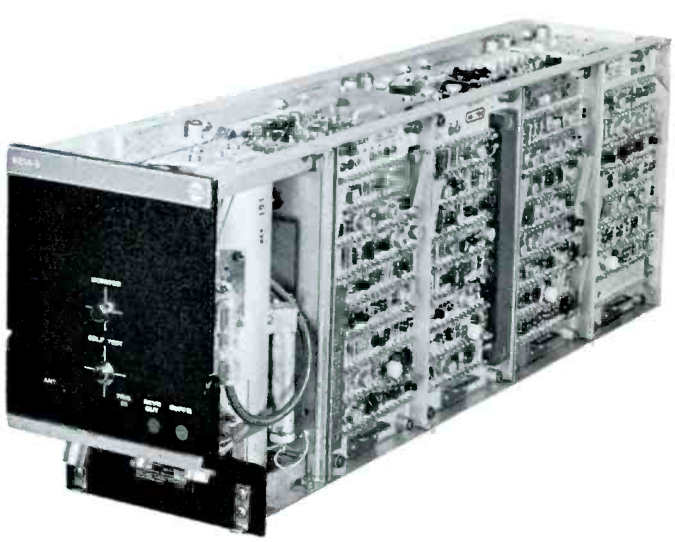


Figure 4 — Decoder Module.

omnidirectional antenna, located with the SSR, transmits a 0.8-microsecond-wide reference pulse (P2) for sidelobe suppression. The P2 pulse is used, in amplitude comparison with P1, to determine whether or not the interrogation is valid. A two-pulse interrogation in a three-pulse circuit is always accepted as a valid interrogation. The three-pulse method of interrogation is used in the U.S. and Canada. It is anticipated that the three pulse system will be universal in a few years.

The two-pulse method of sidelobe suppression provides for an interrogation containing only two pulses. The SSR station transmits a pulse pair interrogation that utilizes a rotating directional antenna and fixed omnidirectional antenna radiations. Pulse spacing between P1 and P3 is determined by the mode of operation. There is no P2 pulse in the two pulse system. The first pulse (P1) is transmitted by the omnidirectional antenna. The last pulse (P3) is transmitted by the directional rotating antenna and is used, in amplitude comparison with P1, to determine whether or not the interrogation is valid. The two-pulse method of interrogation is presently used in Britain. The two-pulse sidelobe suppression circuit is an optional feature of the 621A-3.

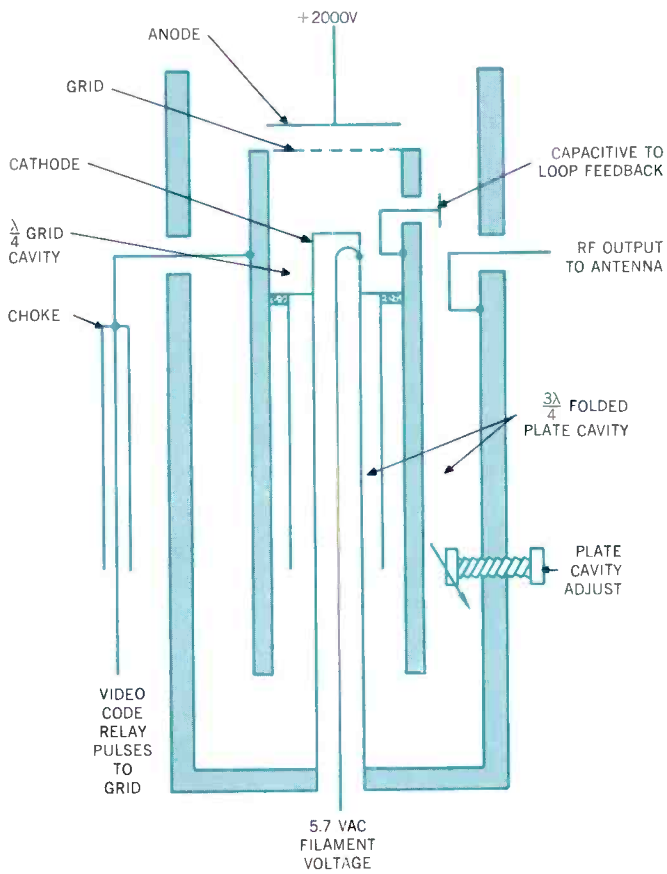
RF Cavities

The 621A-3 uses a Machlett ML-7815 mounted in a 3/4 wave "double folded back" cavity. The 3/4 wave cavity results in a higher Q with the cavity loaded. The high Q provides increased stability for the transmitter frequency. However, the higher Q also requires a tube having greater power capability.

Grid pulse modulation techniques, for the transmitter tube, allow use of a transistorized modulator and eliminate the

Figure 5 — Tube Equivalent Circuit.
For the 621A-3 ATC Transponder, the mounted ML-7815 employs two cavities, one fixed 1/4 wavelength cavity in the grid and the second a variable 3/4 wavelength cavity in the plate circuit. The capacitance of the plate tank is variable to allow adjusting of the output frequency. Feedback, to sustain oscillations in the circuit, is provided through capacitive-plate to inductive-loop coupling in the grid circuit. The output rf pulse is inductively coupled out of the 3/4 wave "double folded back" plate cavity to the antenna.

Figure 5 — Transmitter (with ML-7815) Equivalent Circuit.



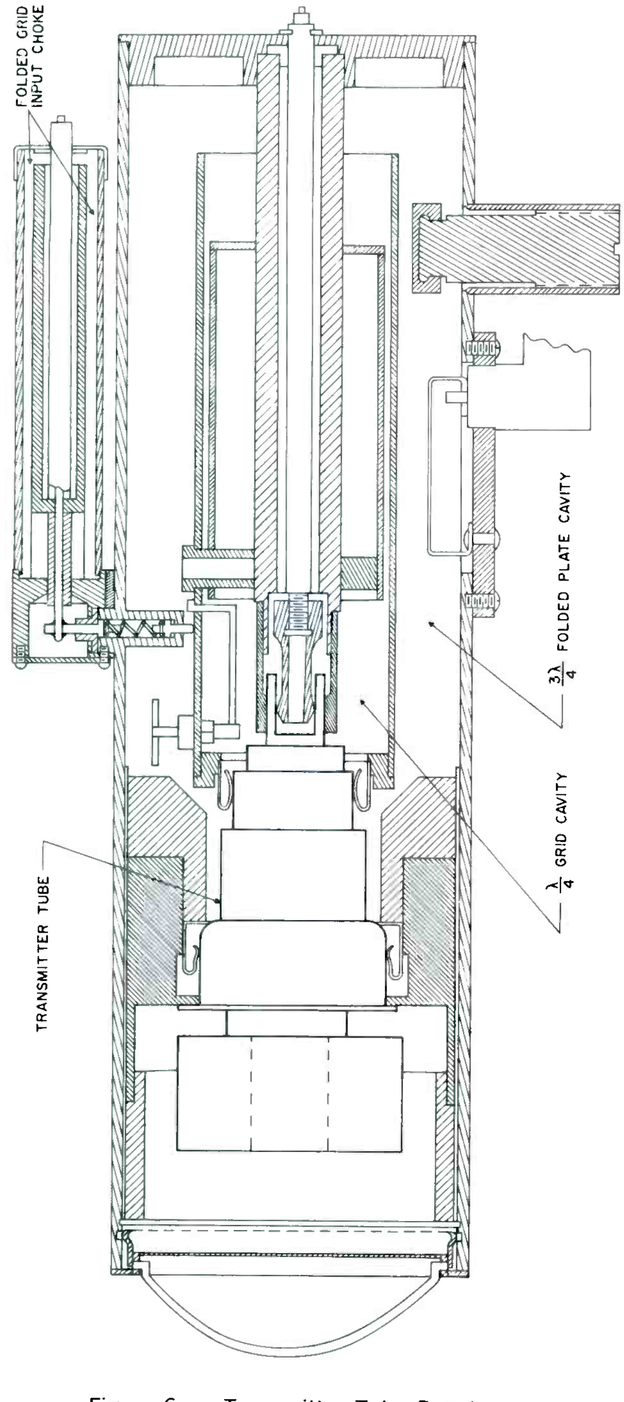


Figure 6 — Transmitter Tube Drawing.

For several years planar transmitting tubes similar to the 2C39 have been used in airborne navigational equipment. New and more stringent requirements have caused continued tube research and improvement. Machlett's research has resulted in the development of the ML-7815. Utilizing the modern Phormat Cathode, the ML-7815 is capable of higher dc plate voltages without destroying the cathode coating. Collins Radio Company selected the ML-7815 as meeting the reliability requirements necessary for the 621A-3 ATC Transponder and the 860E-2 DME.

need for an elaborate plate pulsing power supply. The tube used in this type of equipment must be extremely reliable and have a long life expectancy. The Machlett planar triode ML-7815 was selected for these qualities.

DME

Perhaps the greatest single advance in achieving air navigational safety and efficient air traffic control was taken by the mandatory addition of DME (Distance Measuring Equipment) to commercial air navigation. A focal point of close observation in 1960, DME was given Air Transport of America sanction in a conference held January 19, 1961. The members of the Special Airlines Operations Conference, held in Chicago, determined then that aircraft operated by commercial carriers must have DME.

The action of this committee was justified, and it has been subsequently proven that the airways have been made safer through the use of DME; in addition, the airlines have found DME to be a money saving device. Some of the safety-money-time savings aspects of the DME include:

1. A more precise location of checkpoints than is possible using the intersection of two VOR radials.
2. Allows the pilot to report the exact location of storm cells, when used with weather radar.
3. DME allows approximately a 5 to 1 reduction in enroute separation standards used by ATC.
4. DME allows approximately a 4 to 1 reduction in separation between aircraft departing from a terminal area.
5. Allows back-course ILS let-downs under low ceilings when accurate distance information can effectively replace the glide slope information.
6. Permits quick accurate computation of upper winds.
7. Eliminates procedural turns in some ILS approaches.
8. Better holding patterns.
9. Instant positive position indication (when used with a VOR system).

DME is an active tool of the pilot and a passive tool of the ground controller. The pilot has constant reference to this tool and, since the ground controller is aware of this, the controller can give directions using this active tool as a reference. An example of this is through the use of holding patterns. Previously, holding patterns were established through the use of either time flights or land mark references. The ground controller would for example direct the pilot to fly in one direction for three minutes, turn, then fly in the opposite direction for three minutes. If the day was clear the pilot could be directed to fly to a particular land mark, turn and fly to another land mark and to hold that pattern until told to land.

These methods were, at best, poor. The visual (land mark) method depends on a clear day and the number of such land marks available. And, the proper spacing of land marks is definitely a limiting factor. Flying for a certain number of minutes in a specified direction is problematic

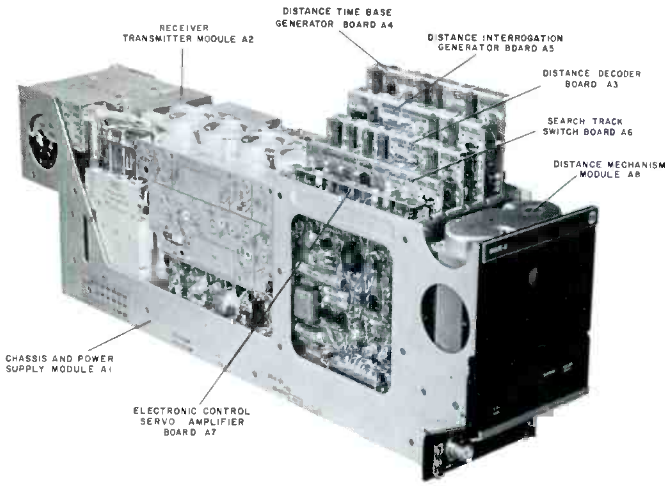


Figure 7 — DME with Dust Cover Removed.

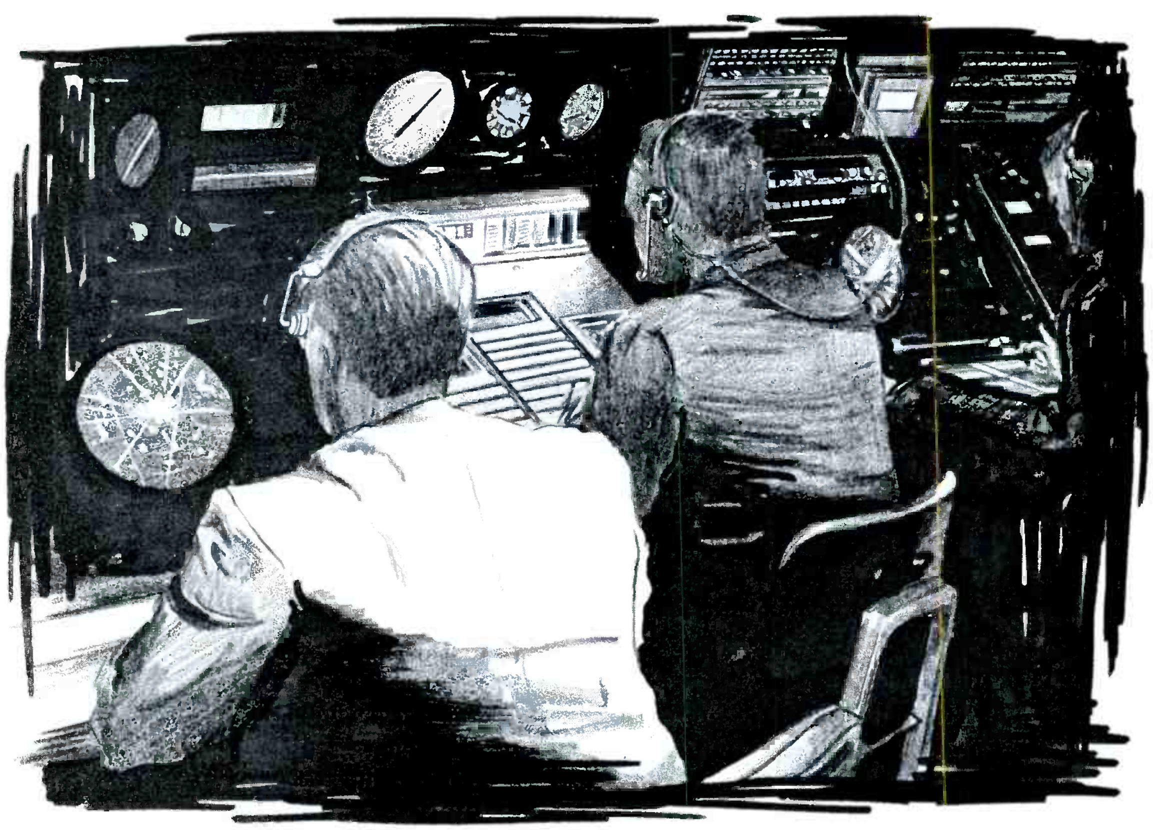
from the aspect of aircraft speed deviation. A jet aircraft will fly more miles than a piston aircraft will, over a given amount of time. Airspace is, therefore, not controlled when these two holding methods are used.

Using DME with a VOR equipped aircraft, the controller can designate the exact distances the aircraft may fly from the VOR and the VOR radial that may be used. Using the DME the pilot can hold this prescribed air pattern. By using this tighter control device, the aircraft becomes safer and safety is essential.

Prior to the requirement for DME, pilots were asked their opinion of the ATC probems; their replies supported the need for DME. One pilot remarked: "ATC procedures in high density areas are woefully inadequate and if DME is the missing link it is badly needed." Since that time in early 1961, DME has proved itself.

DME, How It Works

The distance measuring operation begins when the transmitter portion of the 860E-2 DME transmits a pair of interrogation pulses. These interrogation pulses are received by the selected TACAN or VORTAC ground station. The ground station, after a fixed time delay, transmits a pair of reply pulses. The fixed delay time is used to standardize the inherent delay in every piece of electronic equipment. These reply pulses are received and detected in the receiver portion of the 860E-2 DME and applied to the computing circuits. The computing circuits measure the time interval between the transmission of the interrogation pulses and the reception of the reply pulses. The time interval, which is proportional to the slant distance between the aircraft and the ground station, is converted to distance information for display on the DME distance indicator.



The DME ground station, called a VORTAC station, consists of a TACAN station and a VOR transmitter. The VOR transmitter provides bearing information to aircraft equipped with VOR receivers. A TACAN ground station has the capabilities to reply to DME interrogation signals and also to transmit bearing information and identification signals. The bearing information consists of amplitude-modulated pulses and is used mainly by the military as a source of bearing data.

The 860E-2 DME

The 860E-2 has several new and important features. With the exception of five tubes, the circuits of the DME are completely solid state. Solid state components require less space and weigh less. Consequently, Collins was able to add additional circuits with new functions and refine existing DME circuits. Solid state components require less cooling (no filaments), less power, and extend the reliability of the system. Four of the tubes used are the rf power amplifiers. These amplifiers are Machlett ML-7815 planar triodes and are operated at a very conservative level which extends the operating time. Life tests run with the ML-7815 have produced rather interesting results. The tubes were placed in test fixtures using the general circuit configuration of the 860E-2. The tubes have run over 3000 hours so far with no measurable change in the tube characteristics.

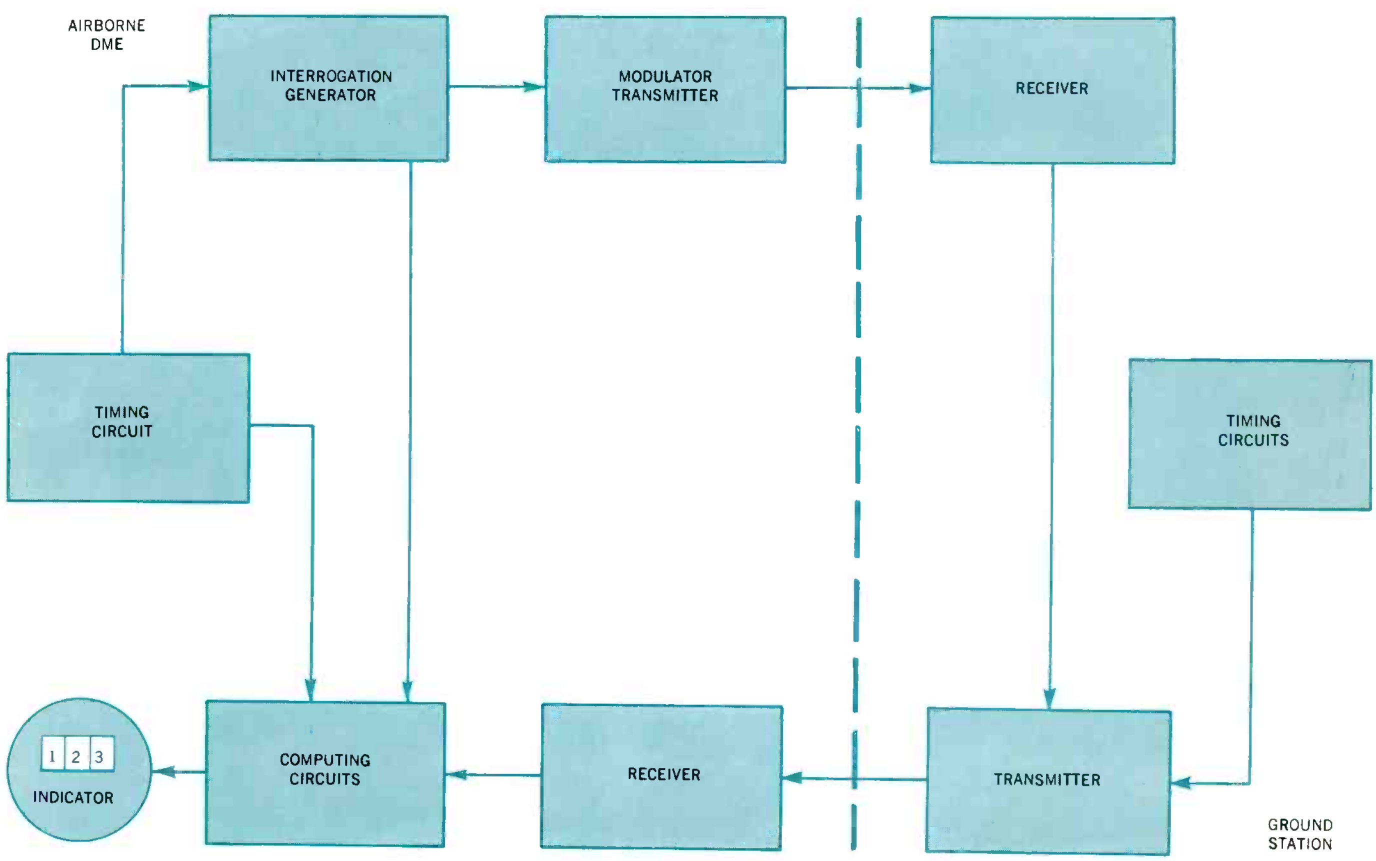
The memory circuit used in the 860E-2 permits the user to select either a velocity or static memory for the system by movement of internal jumper wires. With the velocity memory, and when track is lost, the distance indicator continues to track a synthetic signal at the same rate as the original signal before loss. With static memory, the distance indicator is locked on the same point during memory at the last distance displayed before the signal was lost.

Obsolescence of the 860E-2 is minimized through the use of such features as the built-in split channel circuit. Present DME channel requirements are satisfied by the use of 126 channels. Because of the ever increasing use of air transportation, however, DME ground facility density will increase for a given area. Therefore, by simply changing a jumper wire in the 860E-2, accommodation is made for 252 channels. No other circuit modification is necessary.

RF Cavities of the 860E-2

The 860E-2 rf cavities consist of four plate pulsed amplifiers in cascade. Low level cw rf is supplied to the input circuit of the first amplifier. When the high voltage pulse is supplied to the anode of the amplifier, the applied cw is amplified. The pulsed output is amplified in sequence by the following three plate pulsed amplifiers. Each successive stage

Figure 8 — DME System Block Diagram.



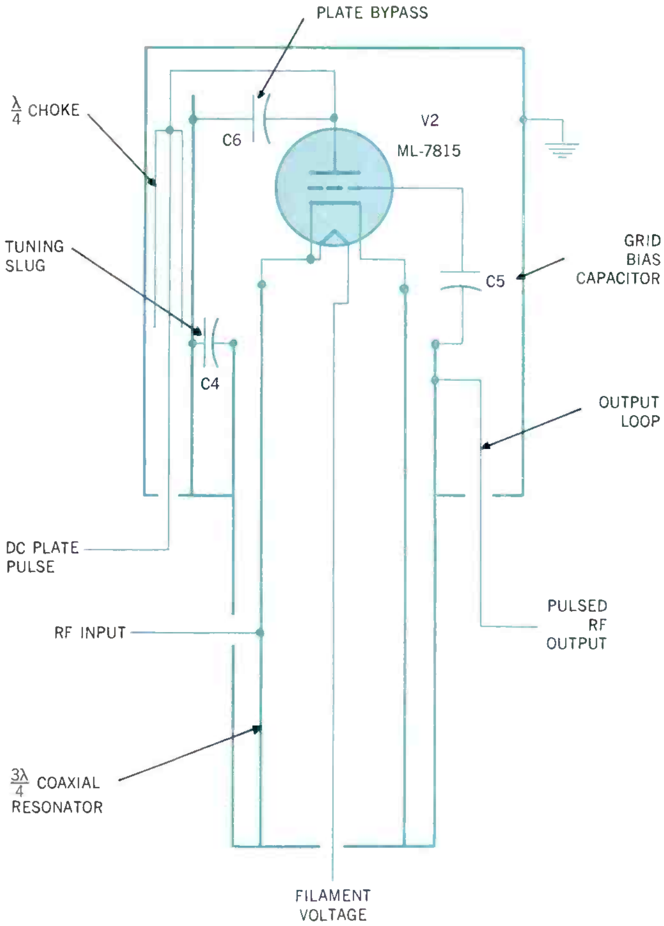


Figure 9 — ML-7815 Cavity High Frequency Equivalent Circuit.

increases the amplitude of the pulsed rf to the output stage. Collins has designed this circuit so that when the cavity tuning is peaked the output power will be approximately 2000 watts. This allows a 3 db margin over the published output power rating of 1000 watts, to accommodate tracking errors and provide for tube aging.

A ¾ wavelength coaxial line section (Figure 9) is used at the input of each amplifier. The coaxial section provides impedance matching and rf isolation for the filament circuit. The grid current caused by the rf is rectified by the cathode-to-grid action charging grid capacitor C11. This charge provides the grid bias for the ML-7815. The output circuit is a ¼ wave coaxial resonator. The output is tuned by adjusting C10. Capacitor C10 consists of the capacitance between the inner and outer conductors of the resonator as provided by the tuning slug. The resonant frequency of the output coaxial resonator is varied by the axial position of the tuning slug.

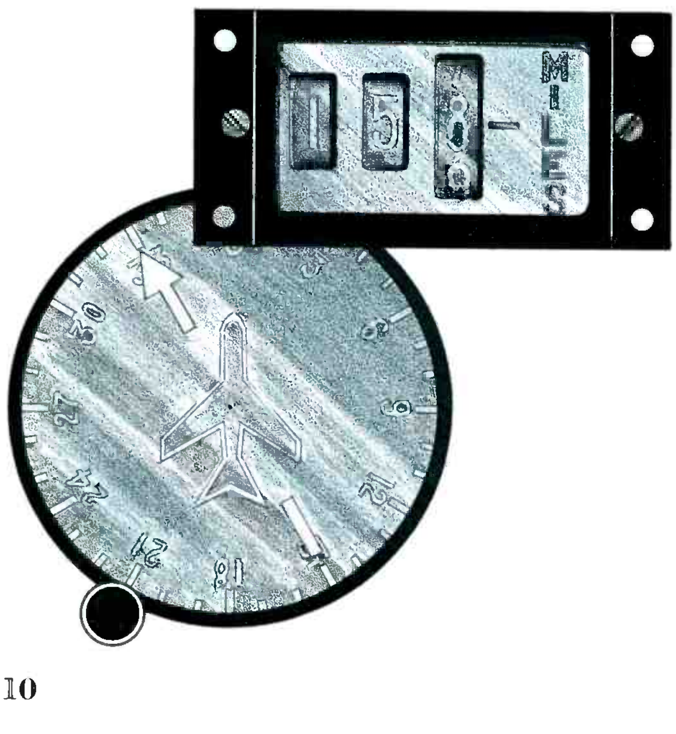
The plate supply voltage is applied through a quarter wave choke to the ML-7815 anode. The quarter wave choke reflects an open circuit to rf. Consequently, rf isolation to the anode supply is adequately provided, and rf radiation from the anode lead is kept to a very low level.

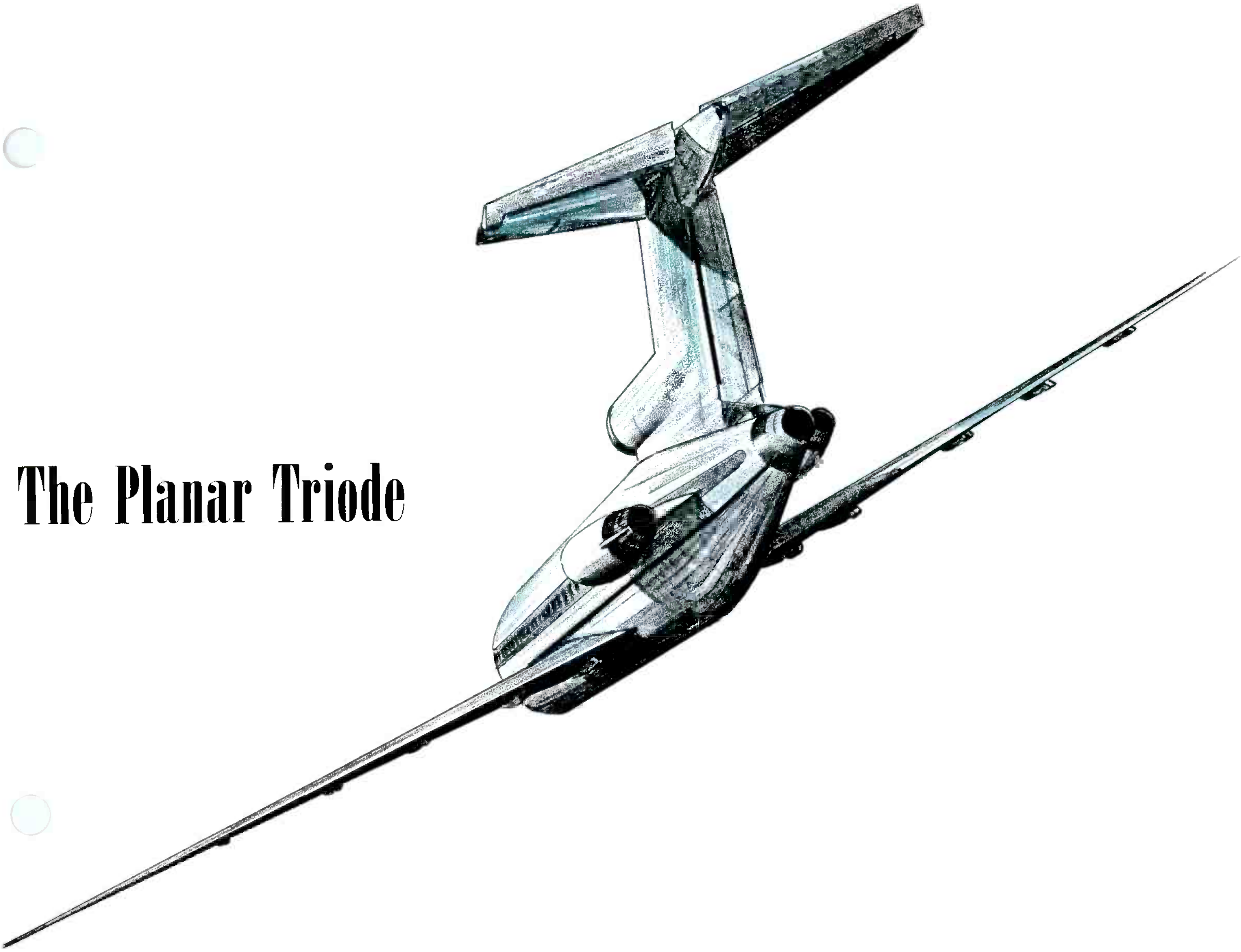
• • •

Through the evolution of improved techniques in tube design and processing, Machlett Laboratories maintains pace with the requirements of the air industry by consistent dependable quality. This is evidenced by the development of the ML-7815, which is standard for both the Collins Radio Company 860E-2 DME and the 621A-3 ATC Transponder.

A Co-incident Evolution: Avionics and

By
HENRY EGGERDING,
Senior Project Engineer
Commercial Avionics
ITT Federal Laboratories





The Planar Triode

Today's air traffic control system requires accurate aircraft position reporting and planning to provide the air travel safety margin we have come to expect. The need for system improvements and the tightening of accuracy tolerances evolves from increasing air traffic density, high speed jet aircraft operation and even higher speed supersonic transport programming.

Aircraft position is determined by three parameters:

(a) Altitude.

(b) Flight track azimuth with reference to a fixed geographic location.

(c) Distance from a fixed geographic location.

The pressure or barometric altimeter provides the first of these parameters reasonably satisfactorily and is used to establish and maintain flight levels for ATC purposes. If a common geographic location is used for (b) and (c) above, we have the elements of a polar coordinate navigation system and it is upon this rho-theta concept that the most widely accepted modern, short range navigation systems are based. (See Figure 1). Since the three broad classes of aircraft, namely general aviation, airline, and military share the same airspace, it is almost essential that a common system giving rho-theta information be available to these users.

As a matter of interesting history, the four course low frequency A/N range system came into use in 1929. In spite of its limitations of only four flight tracks and severe static interference susceptibility, due to its frequency range of 200 to 400 kc's, it served well for many years, but is now obsolete.

The VOR (VHF Omnidirectional Range) which replaced it, gives an unlimited number of flight tracks over 360°. In its frequency range of 108 to 118 mc, it is essentially static free, and it provides precision visual guidance and aural identification in contrast to the purely aural guidance of the A/N range.

These systems provide flight tracks, but no direct information of position along the track. As a matter of fact, the majority of any pilot's cockpit time for the past two decades has been devoted to resolving aircraft position, or establishing the rho element in the purely "theta" systems that have been available to him.

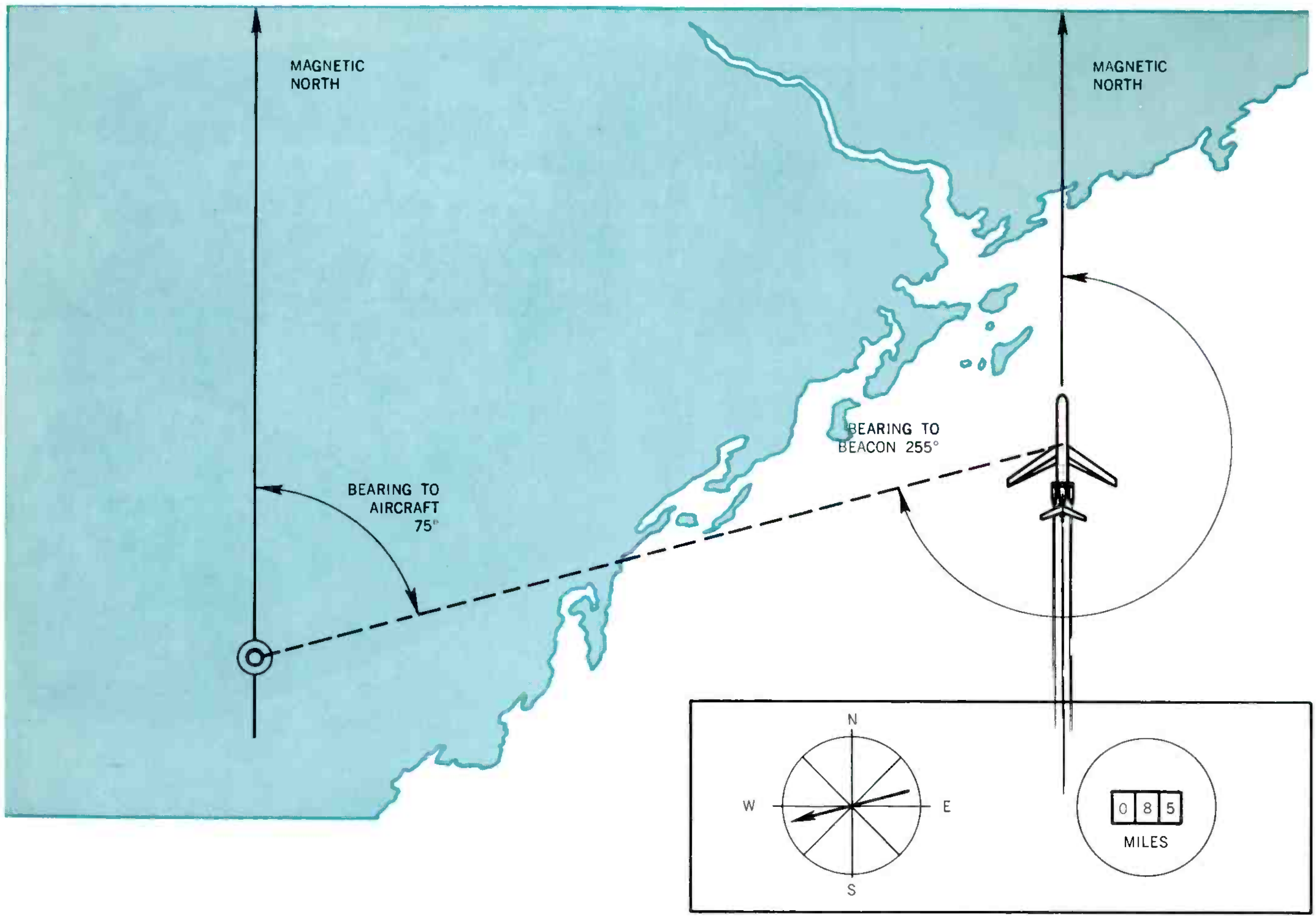


Figure 1 — RHO-THETA Diagram.

The Development of DME

Radar was widely used in WWII to get direct, accurate, distance information, but the method was a cumbersome one calling for a radar operator, a cathode-ray display, and considerable manipulation. It was obvious to many that if this method could be automated and if the cathode-ray display could be eliminated, we could have a pilot-operated system which would give continuous information of progress along the flight track. The outcome was the system we know today as DME (Distance Measuring Equipment).

DME employs a pulse coding technique whereby an airborne transmitter-receiver in the 960 to 1215 mc band, "interrogates" the ground station which is co-located with the azimuth portion of the system, the VOR station. The DME ground station decodes and replies to the interrogator. Since the airborne unit measures the time interval between its interrogation and receipt of the ground station reply, "miles" can be displayed for pilot use.

The combination of VOR and DME gave a rho-theta system which well filled the needs of non-military users. However, various difficulties in military deployment and utilization prevented it from becoming the common military-civil system. Unique military requirements led ITT Federal Laboratories* to conceive and develop the 126 channel integrated distance/bearing system, known as TACAN (Tactical Aerial Navigation). This pulse coded system also in the 960 to 1215 mc band proved so successful that it received world-wide acceptance and resulted in new industry business in hundreds of millions of dollars. Today some 30 prime TACAN manufacturers and countless suppliers participate in this new business.

VORTAC

The need for co-location of the rho-theta ground stations lead to a system known as VORTAC in which the VOR and TACAN ground stations were co-sited and the military/civil common system was made available. Civil aircraft now use the DME portion of TACAN for distance and the VOR for azimuth, while the military aircraft use full TACAN for both distance and azimuth.

Expansion of the VORTAC DME to provide 252 channels

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*ITT Federal Laboratories, Nutley, N.J., is a Division of International Telephone and Telegraph Corporation.

Figure 2 — AN/APN-34 DME overall view with accessories.

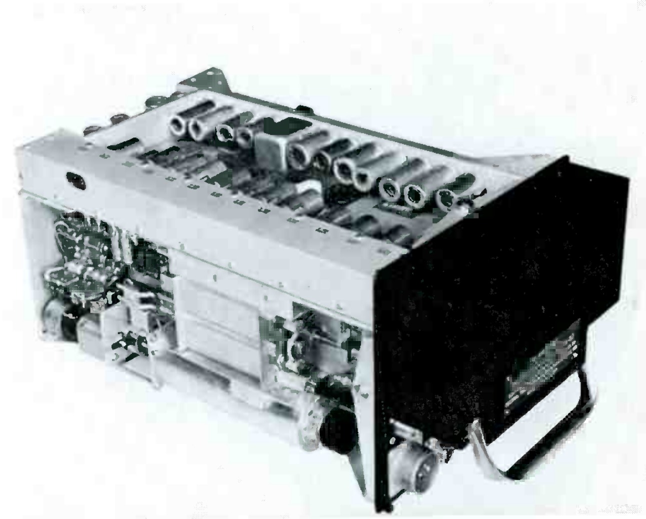


Figure 3 — AN/APN-34 DME without dust cover showing 2C39A oscillator.

Figure 4 — DIA DME overall view with accessories.

Figure 5 — DIA DME without dust cover showing upper portion.

and expansion of TACAN to provide air-to-air Distance/Bearing service is on the immediate horizon. In fact, currently delivered ITT DME-100B's contain the feature of 252 channels (Channel Doubling), while ITT's TACAN now being produced for the Navy, provides the additional feature of air-to-air DME.

Use of DME with ILS (Instrument Landing System) to provide continuous distance to touch-down is an obvious forward step. When a suitable radio altimeter and an automatic throttle control are added, a Low Approach/Auto-Land system will enable landings with lower ceiling and visibility minimums than are currently used. Such a system is now being airline evaluated, using the ITT ALT-200 Low Range Altimeter (1964).

These cockpit rho-theta systems afford the pilot precision navigation which in turn permits better en-route and terminal area traffic control. The end result of all this efficiency improvement is a considerable savings in fuel costs and better on-time performance, both on arrival and departure.

It is interesting to note that the foregoing systems depend heavily on pilot position reports, and this can place considerable burden on the communications channels. Of special concern is the terminal area transition which is to the overall traffic control picture what the boundary conditions represent to an engineering problem. Whereas the rho-theta solution handles the en-route or steady state portion of the air traffic control problem fully, the need for more frequent two-way communication in the terminal area calls for a complementary semi-automatic solution.

The development of the air traffic control transponder system permits wholesale or selective aircraft interrogation and visual identification by traffic control personnel. As it is presently used, pulse coding permits ready identification of individual or of groups of aircraft without requiring voice communications. Through the ultimate use of altitude encoders, position-in-space can be readily established.

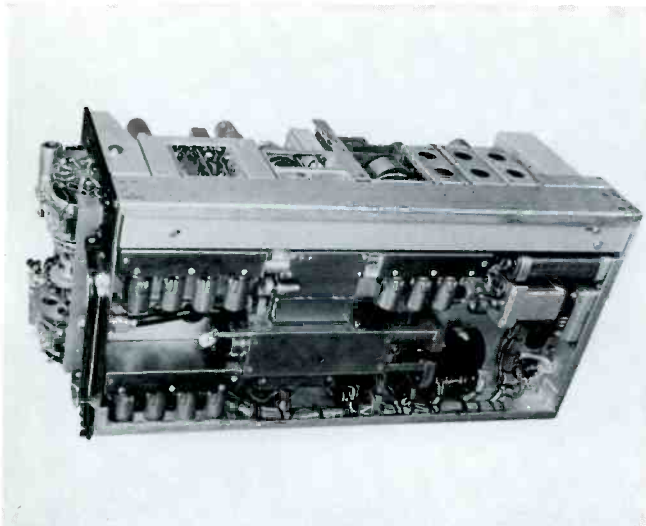


Figure 6 — DIA DME underside showing 2C39A oscillator.

Figure 7 — AFN-3544 airline DME prototype with accessories.

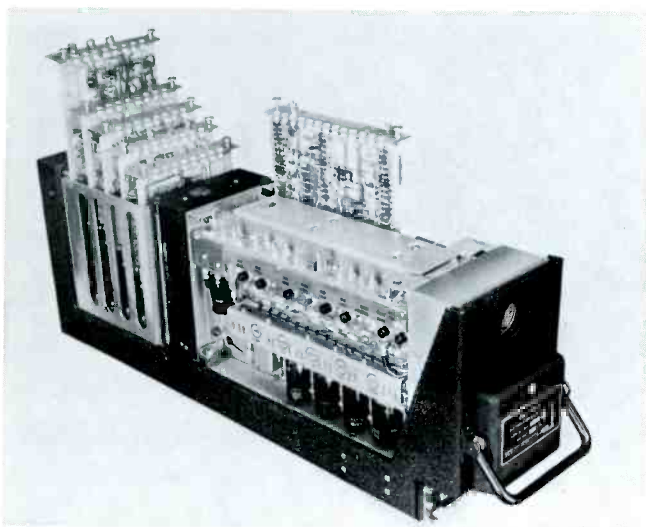


Figure 8 — DME-100A airline DME semi-exploded view.

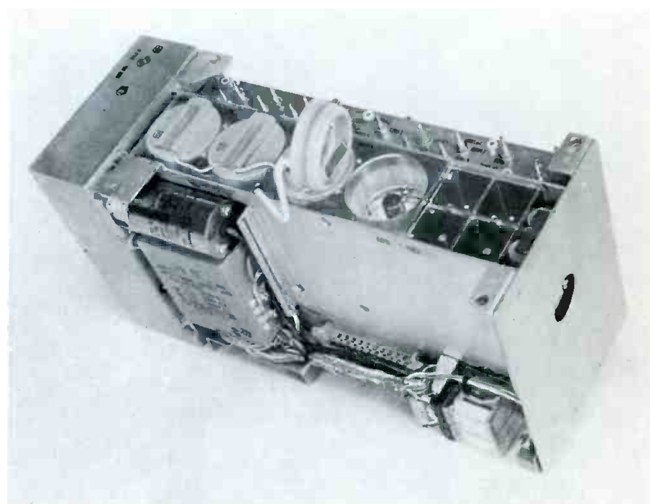


Figure 9 — DME-100A RF Module showing ML-7815.

These two systems are mutually independent and serve to provide the elements of a fully automatic ATC picture.

DME/ATC Transponder Similarities and Differences

The ATC transponder system is an outgrowth of the military IFF system in which an IFF Interrogator is co-located with a Search (Surveillance) Radar. The Interrogator antenna scans with the radar and when transponder equipped targets are "illuminated" by the pulse-coded interrogation, the targets reply on a different frequency (IFF/ATC transponder RF channels, one for each path, share the 950 to 1250 mc band with TACAN, but different pulse codes are used) with a signal which gives target identity, which can consist of a multiplicity of information bits including altitude, trip number and sequence.

Since the DME process starts and ends in the aircraft, the resultant information is immediately and continuously available in the aircraft while in the IFF/ATC case, the process is reversed and the information is present at the radar site. It must now, be relayed "manually" or "orally" to the aircraft to be of use to the pilot. IFF/ATC replies are usually presented on the radar PPI scope and here we have another difference between DME and IFF. It is highly desirable that transponder power output be held within close limits regardless of duty cycle, so that equi-strength signals (for a given range) are available at the output of the Interrogator's receiver and thus, that replies are of equal intensity when seen on the PPI display. DME signals in contrast are amplitude limited before processing to extract the time information so that transmitter power output is of little consequence.

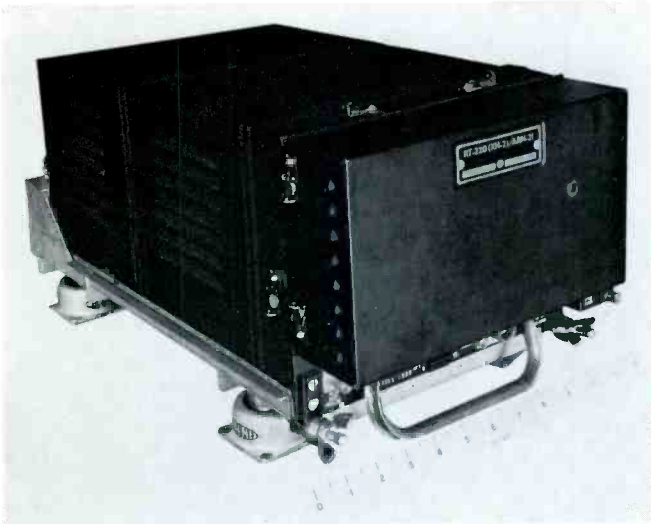


Figure 11 — AN/ARN-21 TACAN in dust cover, on shockmount.

Figure 10 — AIN-102A Distance Indicator for DME-100.

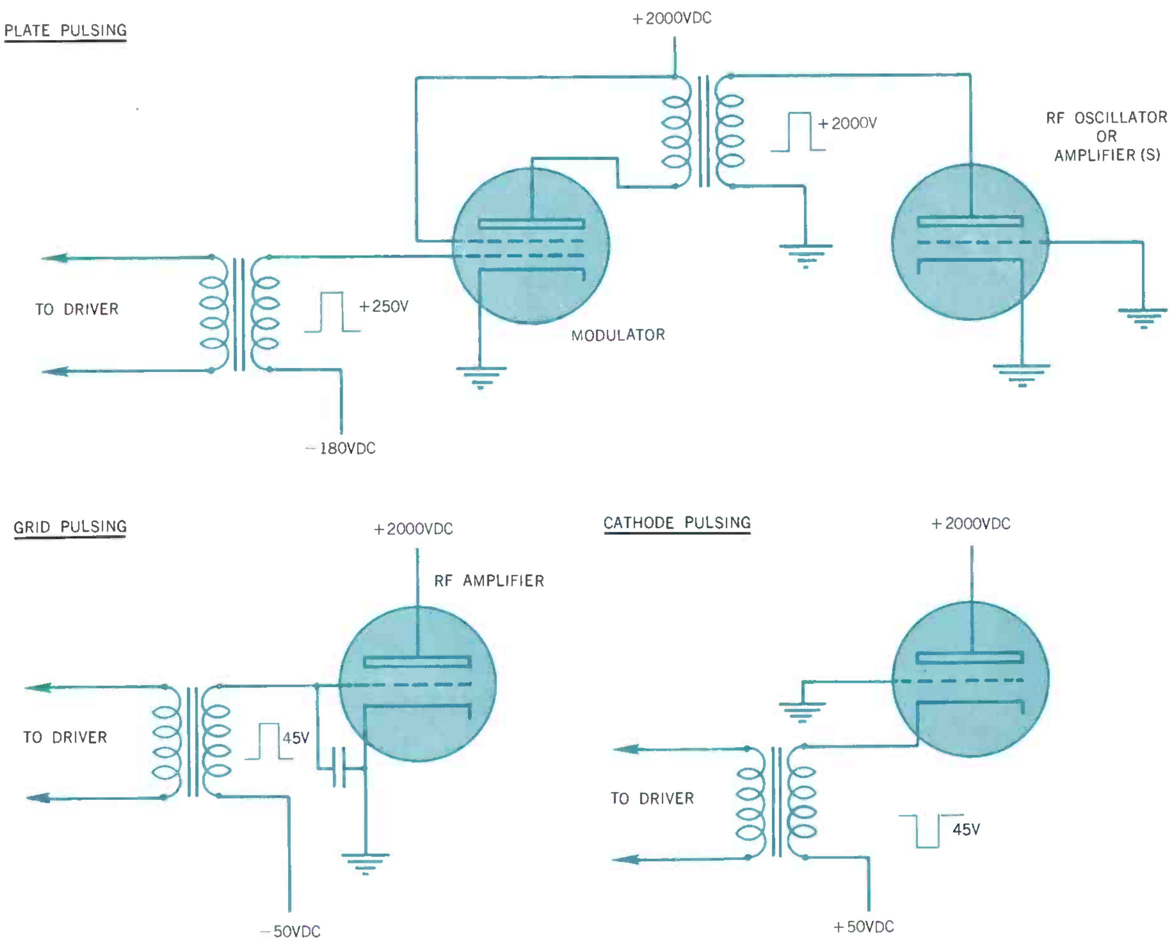


Figure 12 — Modulation methods.

Figure 13 — AFN-125, F-104 TACAN configuration with dust cover.

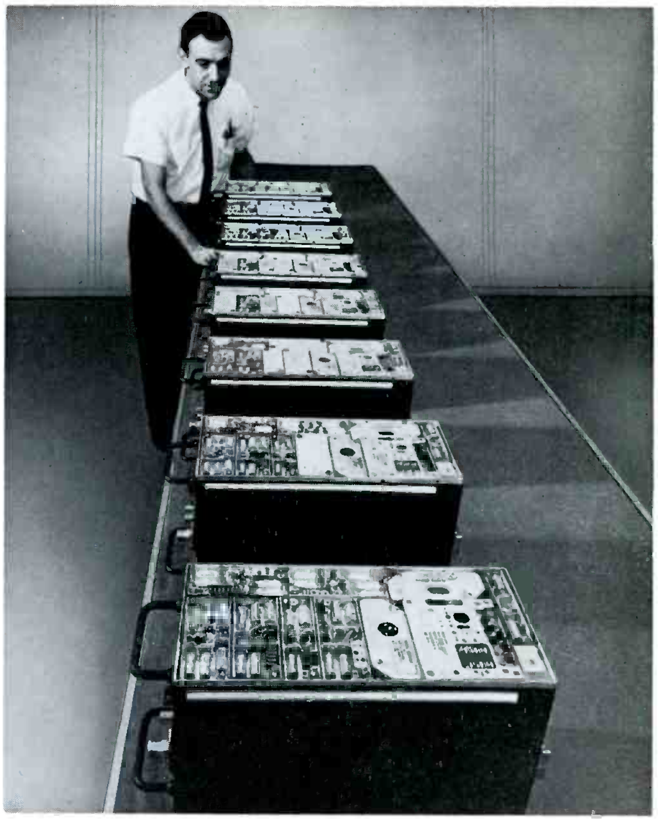


Figure 14 — Latest TACAN units.

In parallel with the evolution of radio navigation aids, an interesting evolution has taken place in the 2C39 planar triode. This glass envelope, external anode tube was designed in the early 1940's as a 100 watt plate dissipation, cw, transmitting tube. In early DME's designed and produced by ITT, it was used as a plate-pulsed oscillator with crystal-referenced AFC. The light DME duty cycle held plate dissipation well below 10 watts, although pulse voltages of between 2 and 3 kilovolts were applied to get power output in the kilowatt region.

TACAN to DME — Design Developments

The first airborne TACAN, the AN/ARN-21 (Sept. 1952) (Figure 11) designed and produced by ITT used a chain of five 2C39A's, again plate pulsed, in a direct crystal multiplier transmitter. (ITT's AN/APX-7, 1952, 1953, used a similar chain). It proved relatively easy to provide enough plate power from the modulator for the single 2C39 pulsed oscillators in the early DME's, but the multi-tube chains (in some cases the multiplier preceding the cascaded 2C39's was also pulsed) in the ARN-21 and the APX-7 required so much modulator power that modulator life was short when a tube of practical size was used. Loss of cathode emission was the predominant failure mode.

Grid Pulsed DME

This modulator tube life problem led ITT to seek a solution when design of the AFN-3544 DME was started late in 1956. In the type of plate pulsing circuit which we had used, a video tetrode with high plate and screen voltages was provided with cut-off bias. When the grid was pulsed "on" by the driver stage, the tetrode's cathode current became plate current for the RF stages. Since the tetrode's cathode emission capacity over a period of time was the limiting factor and since the cathodes of the RF tubes had a large emission capability, therein lay a possible solution. The tetrode was eliminated, its dc plate supply was connected to the RF tube anodes and cut-off bias was applied to the RF tube grids (or to the cathodes in later versions). The former tetrode driver was fed to the RF grids and we thus had "grid pulsing." (See Figure 12). A 5000 hour life test of this principle indicated that it was indeed a usable answer to the modulator problem in spite of the increase in transmitter cavity complexity and cost to allow for the application of the hold-off bias and the turn-on pulse to the RF tubes.

The ceramic 2C39B had appeared by this time and a special version of this tube (the 3CPN10A5), with a finger-grip in place of the unused cooling fins and an extended grid/anode envelope was generated. Later, field experience showed that an emission-life-problem still existed with some of the 3CPN10A5's. Machlett's Phormat cathode came as a timely solution and led to the 7815 incorporating this feature.

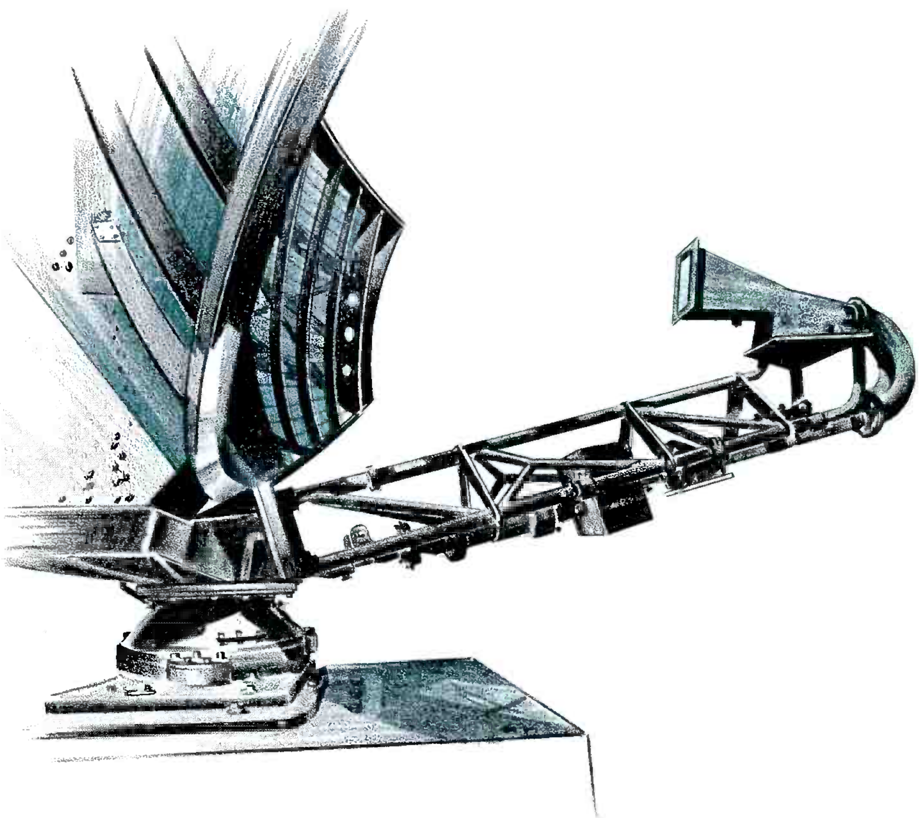
ITT's AFN-125, F-104 configuration, Figure 13 (1960) which followed the AFN-3544 DME (1958) was required to provide more output power over a wider environmental range so the 7698, a high perveance version of the 7815, was developed by Machlett and of course, the Phormat cathode was included in this type also.

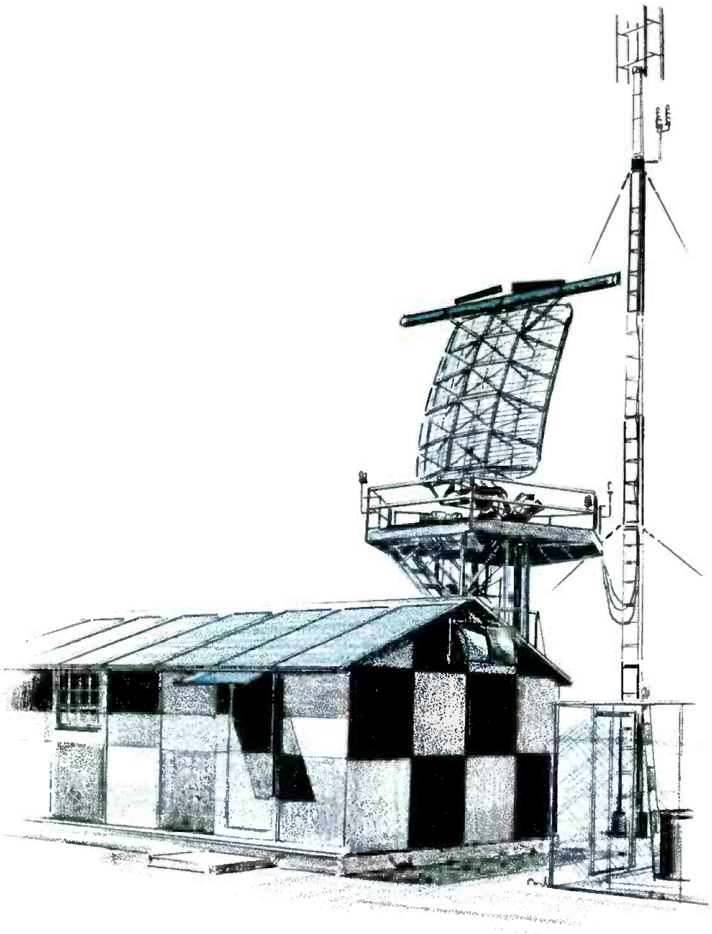
The new airline DME-100B, (1963), solid state, except for the multiplier/transmitter, which followed the AFN-3544 DME as ITT's airline DME, again uses 7815's in the transmitter chain. (See Figure 14).

We have thus come from a fragile, heat sensitive, glass 2C39 with its superfluous, for our use, cooling fins and a limited altitude capability (the AN/ARN-21 and the AN/APX-7 cut power output in half, above 35,000 feet to avoid arc-overs) to the 7815 and 7698. These tubes have proven much more uniform and rugged with the absence of cooling fins allowing more compact cavities. The Phormat cathode makes a substantial contribution to the life expectancy of more than 2000 hours for these transmitting tubes in spite of the demands of grid pulsing.

The 2000 hours life figure mentioned above is a significant factor in scheduled airline operation where premature failures result in spare equipment needs at remote locations, where in some instances, airline-owned radio repair facilities are non-existent. The spare equipment provisioning costs materially influence the equipment "buy" decisions since airline operating costs are materially affected by an equipment's mean-time-between-failures (MTBF).

Thus the equipment supplier shares a very important responsibility with the tube manufacturer in ever working towards better MTBF's — better still, lower customer costs. Transcending even this important factor is the continually increasing need for high reliability in an air safety environment.





Wilcox Transponders

Introduction

The increase of air traffic, both civil and military, has necessitated the use of a system for positive control of the separation of active aircraft in a safe efficient manner. The system is a secondary surveillance radar more commonly known as the Air Traffic Control Radar Beacon System (ATCRBS).

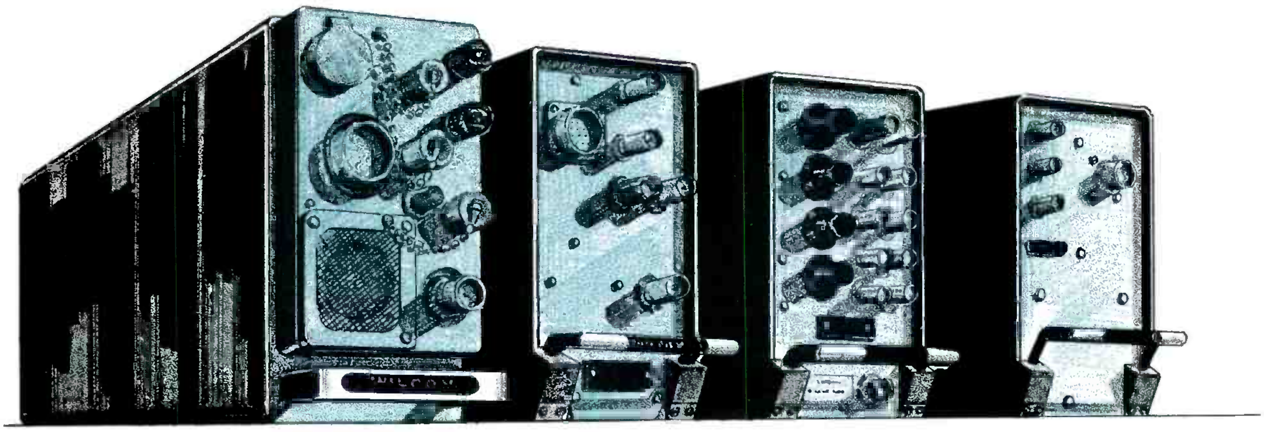
The ATCRBS in use today was developed in World War II, due to a need for identifying an aircraft as friend or foe. This system used equipment on the ground to transmit an interrogation signal to the aircraft and a receiver-transmitter in the aircraft to transmit a response back to the ground station. The interrogation signal was received by the aircraft receiver and decoded. If the receiver-transmitter in the aircraft were set to respond to the interrogation, the transmitter sent a coded reply signal to the ground station. The signal was received and decoded by the ground equipment and presented on a radar Plan Position Indicator (PPI) indicator. If the response conformed with the established coding, the aircraft was assumed to be friendly. This was known as an IFF (Identification Friend or Foe) System and has been the basis for the development of the ATCRBS.

The function of the radar beacon in today's environment of air traffic control is to provide positive indentification of individual aircraft rather than identification friend or foe. Normally a ground radar PPI display shows only azimuth and distance of aircraft in the area. However, the traffic controller needs a three-dimensional picture to adequately maintain aircraft separation. To achieve this the ground station transmits two modes of interrogation, one mode for range and azimuth, another mode for altitude or height. The altitude information is given to the aircraft beacon by a separate altimeter in the aircraft. The altimeter pulse codes the aircraft beacon and upon a proper mode of interrogation, replies to the ground station with flight altitude information.

Thereby we have an extremely versatile secondary surveillance radar system which for civil usage provides positive three-dimensional control and in a military usage supplies IFF information.

1955: The beginning of the Beacon program

The Wilcox Electric Company designed an Air Traffic Control Radar Beacon in 1955, which was designated the Wilcox 714A. Since that time the company has maintained a successful development program which has resulted in those equipments shown in Figure 1. The 714D, 814B



for Air Traffic Control

By RICHARD W. DONOVAN,
Project Group Leader,
Wilcox Electric Co., Inc.

and 914A are for commercial airline or civil use.

The 714D is a hybrid unit in that vacuum tubes and transistors are used extensively. The 814 General Aviation Transponder (GAT) evolved under an FAA development contract for service in the general aviation or executive aircraft industry. Nearly 1000 of the 814 units have been produced. The 914X is a transistorized all mode capability military IFF transponder designed to MIL-E-5400, Class II, and the U.S. National Standard ATCRBS specification. The 914 transponder is presently in production with deliveries starting in May for 250 units.

Figure 2 shows the 914 Transponder with the covers removed. The basic construction is modular, with plug-in assemblies. Figure 3 is a view showing some of the modules removed and illustrating the ease of maintenance and accessibility designed into the 914.

Figure 4 is the 814 Transponder with covers removed. This unit utilizes hinged assemblies which swing out for accessibility and maintenance, rather than plug-in.

The 814 GAT is designed as a low cost, low weight (11 lbs.) transponder meeting the FAA TSO-C74 requirements. It contains both Mode A and Mode C interrogation modes, each having 4096 possible reply codes. The transmitter output power is a nominal 500 watts peak. The 814 is certified to an environment of —15°C to +55°C and 30,000 feet altitude. On special applications, modification can be made which allows the unit to operate at 50,000 feet altitude.

The 914 is the latest design now in production by Wilcox. Silicon transistors are used exclusively to permit operation under greater temperature extremes. The unit is designed to meet ARINC 532D and FAA TSO-C74, Category A. The unit is packaged in a ½ ATR long form factor weighing 18 pounds. This form factor is very ample allowing a great deal of freedom to provide accessibility in the interest of maintenance. Reliability has been a prime consideration in selecting the components and the final design. Reliability analysis has shown that a guaranteed aircraft removal rate of 2000 hours can be given. What has made this rate possible has been in selection of components which have low failure rates. Tantalum capacitors have been minimized and replaced by mylar foils. Moving parts such as relays and switches have been eliminated or replaced by diode switching and semiconductor devices. All heat generating devices such as the transmitter and voltage regulator are provided special heat sinks and dissipating areas, allowing heat conduction to the external surfaces rather than within. The whole rear panel is a finned casting and is used as a heat sink for the transistorized dc line regulator.

A self test module is included within the equipment. Dynamic transponder operation is checked and monitored while in flight, or if desirable a pre-flight test is made. The testor generates Mode A, 1030 mc rf pulses which interrogate the transponder. If the transponder is operational, then the transmitter will be fired and the tester receives the 1090 mc energy of the transmitted reply pulses and cause a light to indicate proper operation. In this manner receiver frequency, receiver sensitivity, decoder, encoder and transmitter power are tested and monitored to establish limits. Experience has shown that these tests give a very high degree of assurance that the transponder is completely operational.

The receiver front end assembly is fixed tuned, requiring no maintenance adjustment. The receiver IF amplifier incorporates a band pass filter for selectivity with all stages transistorized.

Transmitter Modules

The transmitter modules shown in Figure 5 are for the 914 and 814. The lower one is for the 814 GAT Transponder. The black body transmitter assembly is for the 914 and also contains the power supply for the transponder. Both cavities are die cast and silver plated. The upper cavity is an aluminum casting while the lower is a brass casting. Since both cavities are very similar in internal construction, only the 914 cavity will be discussed. The 914 cavity cross sectional view is shown in Figure 6. The basic difference between the 814 and 914 cavities is that the power supply is part of the assembly in the 914. Construction is such as to dissipate the maximum amount of heat by radiation, as at high altitudes very little air is available to conduct heat. The castings are provided with "O" ring seals

Figure 1 — Air Traffic Control Radar Beacons developed by The Wilcox Electric Company in a program beginning in 1955 with the Model 714A. From the left: Model 714D, 814B and 914A for commercial airline or civil use; Model 914X an all mode unit for military use.

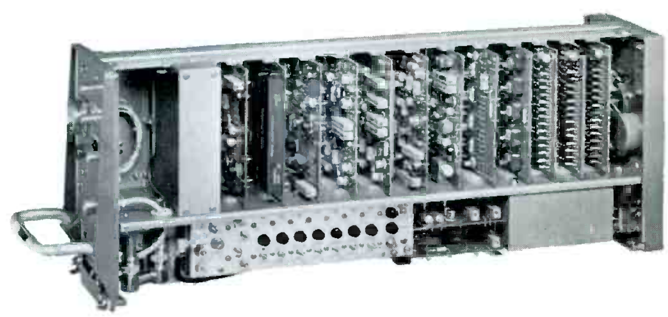


Figure 2 — The 914 Transponder with covers removed.

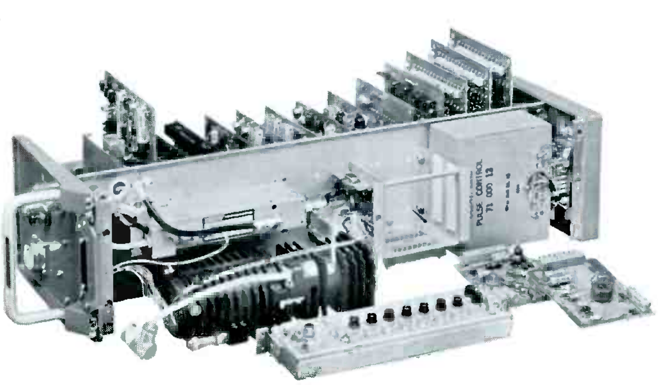


Figure 3 — The 914 Transponder with modules removed.

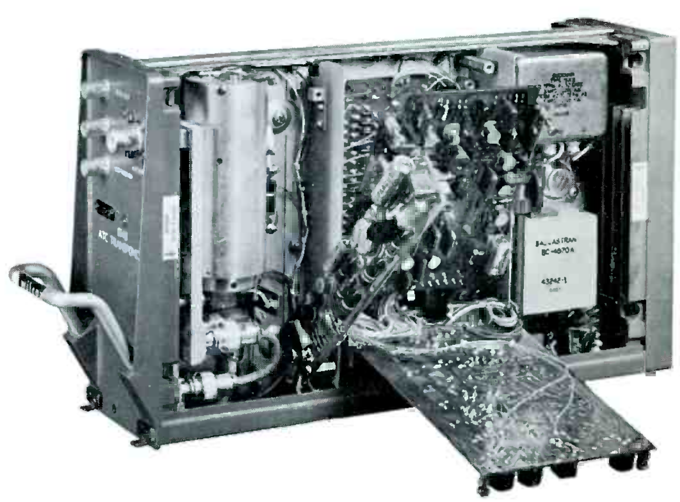


Figure 4 — The 814 GAT Transponder with covers removed. This model utilizes hinged assemblies.

to maintain atmospheric pressure inside the cavity while the external ambient pressure goes up to 80,000 feet. Thus any difficulties from corona or high voltage breakdown are eliminated.

The H.V. power supply section contains a DC to DC converter operating at 10 kilocycles. The converting transformer on the left provides the end seal for this assembly. Transmitter tuning comes out this end also to the front panel for easy accessibility. The high voltage rectifier filter capacitors and bleeder resistors are mounted in a pack shown in Fig. 6 that is keyed and slips into the power supply section casting. The H. V. power supply provides a nominal 2000 volts at 15 ma. and is adjustable in three steps of 1800 volts, 2000 volts and 2200 volts. These adjustable steps allow the transmitter power to be maintained at a nominal 500 watts peak as the tube degrades with life.

Planar Triodes in Beacon

The 914 Transmitter uses a Machlett 7855 while the 814 GAT uses the Machlett 7815. The GAT environmental temperature extremes are much less than those of the 914 and thus the anode temperature stabilized tube is not essential. Both cavities are capacitive coupled into diplexers and then coupled to the antenna transmission line. However, the 914 uses a ferrite isolator between the diplexer and transmitter. The isolator isolates the antenna load from the transmitter by 10 db, allowing a transmission line load mismatch of 4:1 without appreciable frequency shift of the transmitter. The measured frequency shift with a 4:1 VSWR is less than 1.5 mc.

The 914 transmitter design is a grid-separation tuned-plate tuned-grid oscillator using grid pulsing. A constant DC voltage is maintained on the plate of the 7855 triode.

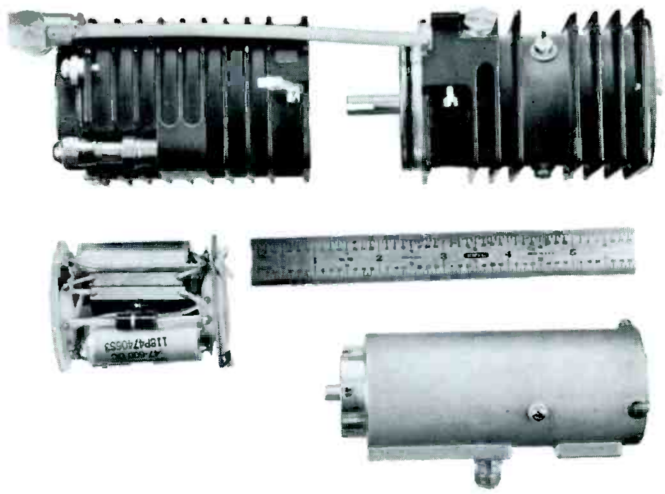
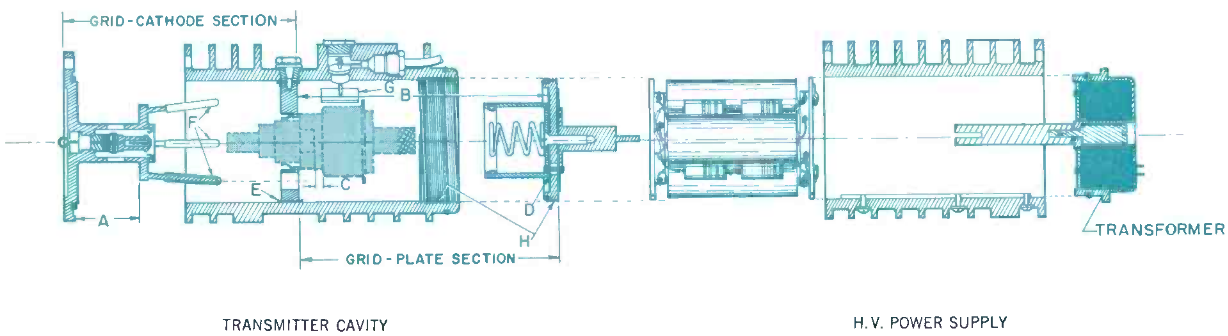


Figure 5 — Transmitter modules for the 914 (upper) and 814 Transponder (lower).

Figure 6 — Cross section view of the 914 cavity.



A – cathode cavity inductance
B – plate cavity inductance
C – grid-to-plate interelectrode capacitance
D – plate by plate capacitance
E – grid by-pass capacity
F – feed back capacity
G – output coupling capacity
H – frequency adjust

The grid is biased beyond cutoff at —100 volts. The modulator pulses the grid 20 volts positive exciting the cavity to its self resonant frequency.

In Figure 6, which shows the transmitter cavity design, cathode assembly A provides the feedback element F, which maintain the proper phase relationship between the grid-cathode section and the grid plate section. Teflon dielectric is slipped over the feedback probes to prevent voltage breakdown. The grid is —100 volts above DC ground, AC ground is provided by the grid by-pass capacity E, which is a teflon tape assembled to the grid and into the casting through a shrink fitting process. In this way constant by-pass capacity, regardless of the mechanical tolerances and temperature differentials, is maintained.

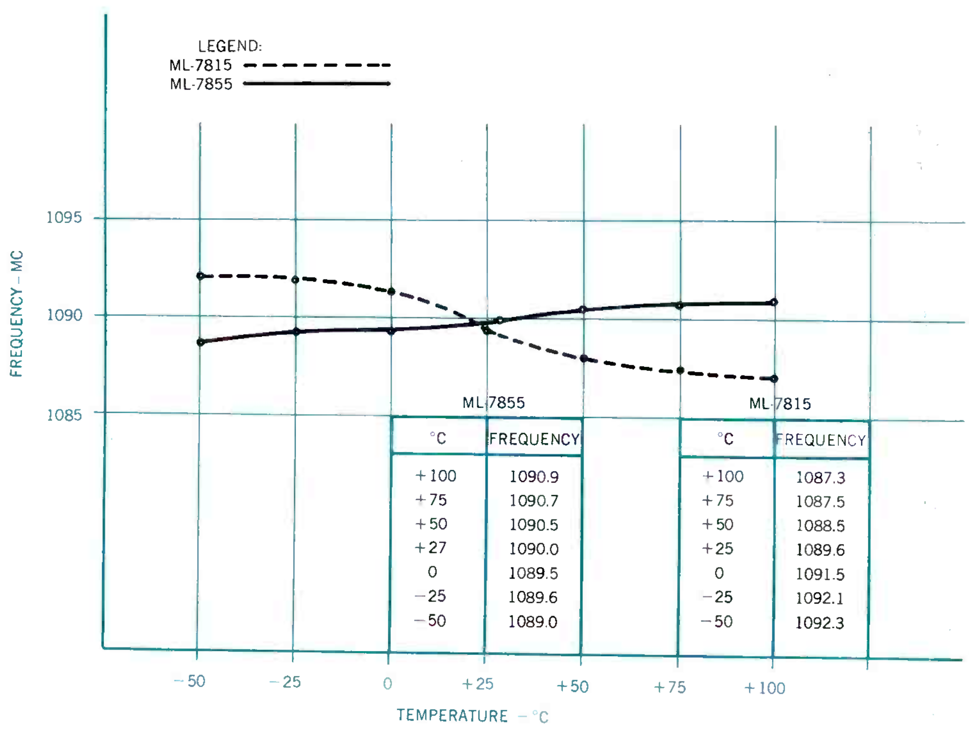
The grid-plate section is tuned by the frequency adjust H and tunes the plate cavity inductance B. The inductance is such as to form parallel resonance with the grid to plate interelectrode capacitance C. The plate is by-passed by 3 mil mica discs, D.

The rf is coupled from the cavity by the capacitive probe G. Since the plate voltage is adjusted in steps to increase power due to the tube degradation, the coupling is fixed and requires no adjustment. The cavity is coupled for a nominal 500 watts which is required for certification, however, during the development it was demonstrated that 1000 watts can be coupled with minor adjustments to the feedback and coupling probes.

Use of Frequency Stable Triodes

Frequency stability of the final cavity designs is shown in Figure 7. Stability has been achieved without the use of special materials such as invar and kovar. The cavities are stress relieved to the full anealed condition of the material prior to final machining. The grid by-pass capacitor is shrink fitted to insure a constant capacity due to any mechanical dimensional changes that may occur throughout the temperature range. The plate by-pass is mica which has excellent mechanical stability through the temperature extremes. The curves are quite significant and illustrate the ability of the 7855 to temperature compensate the Wilcox cavity design. It should be noted that slight modifi-

Figure 7 — Frequency stability of final cavity design. The ML-7855 frequency stable tube is employed to provide this stable characteristic.

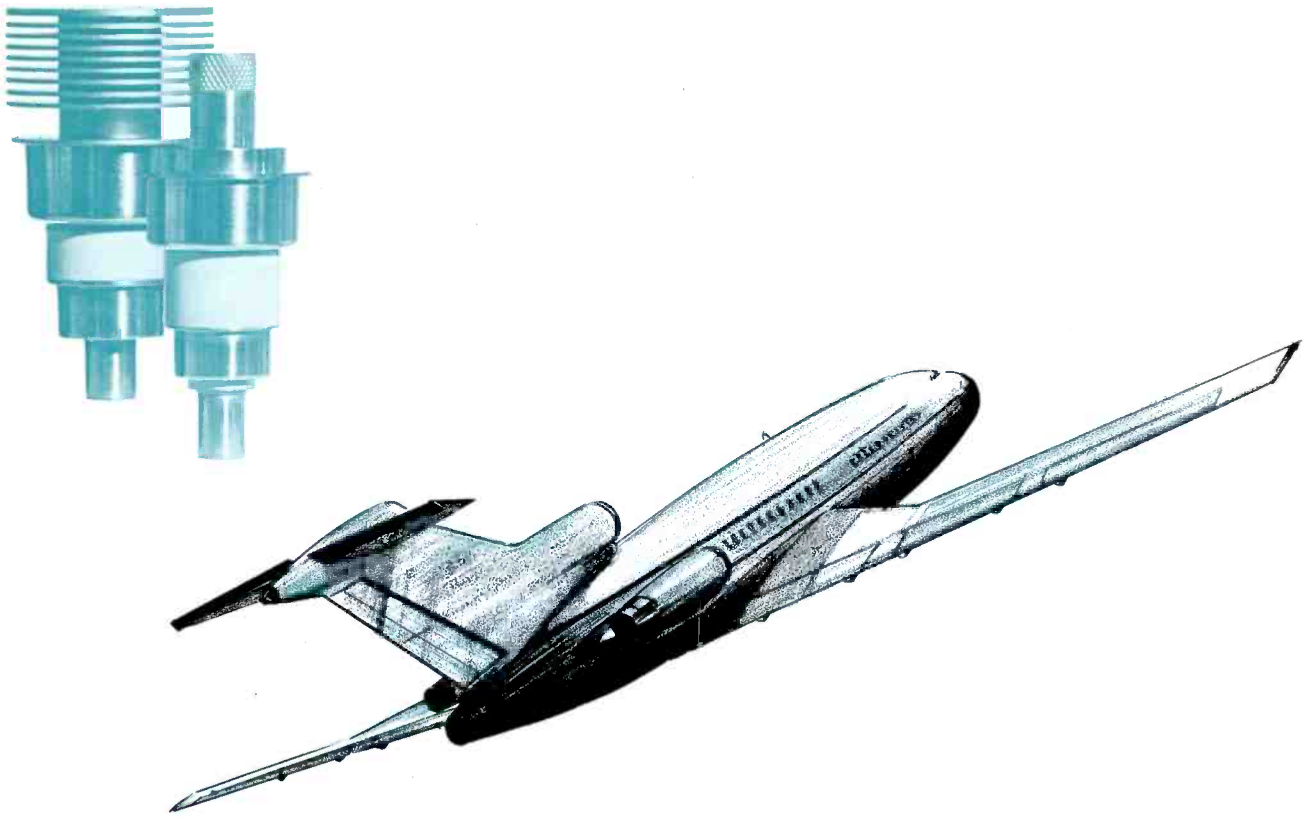


ML 7855

°C	FREQUENCY
+100	1090.9
+75	1090.7
+50	1090.5
+27	1090.0
0	1089.5
−25	1089.6
−50	1089.0

ML 7815

°C	FREQUENCY
+100	1087.3
+75	1087.5
+50	1088.5
+25	1089.6
0	1091.5
−25	1092.1
−50	1092.3



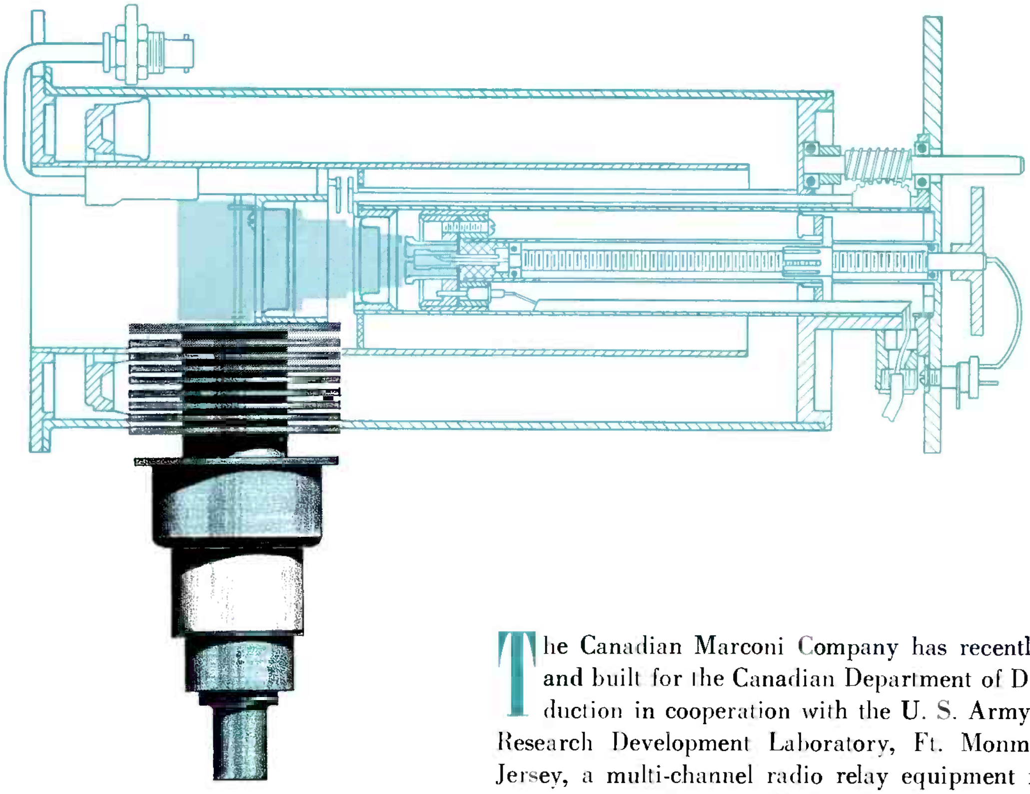
cations to the cathode section was necessary when interchanging the tubes, as they are not dimensionally interchangeable. Electrical performance was essentially the same for both tubes, however, the tuning was adjusted to a shorter length for the 7855.

The 7815 could have been used for the commercial 914 transponder but it was felt a greater margin of stability was desirable as VSWR shift would only add to the total frequency deviation. By using the 7855 tube and combining the frequency shift due to temperature, 4:1 VSWR shift and up to 1% duty cycle shift, the frequency was found to have a maximum excursion around 1090 megacycles of +2.4 mc and —2.5 mc. These measurements are well within the specification and are considered very good under present design standards.

Life tests are in process on 7855's in the cavities at this writing. Present data shows that after 600 hours no degradation is being observed. Life tests on the 7815 in the cavities show life in excess of 1200 hours before degradation takes place. Both of the tubes are being grid pulsed in the same circuit at a 1% duty with a nominal 500 watts coupled out. The filament voltage is operated at 5.8 volts rms.

Conclusion

The controlling of air traffic has been made safer and positive with the use of the Air Traffic Control Transponder. The Wilcox Electric Company has been a leader in developing the ATC Transponder system and in continued development of solid state transponders, both for commercial use and military use. The Wilcox 914 and 814 commercial transponders were discussed. Comparison of the ML-7815 and ML-7855 tubes in a Wilcox designed cavity were described showing the basis for their selection in the 814 GAT and 914 airline transponder. The data and design work for this article was performed within the engineering department at the Wilcox Electric Company, 1400 Chestnut Street, Kansas City, Missouri. Acknowledgement is made to Mr. Forest Nichols, Design Engineer, and Mr. John Campbell, Design Technician, for their able assistance in the design and for taking the data as a part of this article.



The Canadian Marconi Company has recently designed and built for the Canadian Department of Defense Production in cooperation with the U. S. Army Electronic Research Development Laboratory, Ft. Monmouth, New Jersey, a multi-channel radio relay equipment for tactical use. To obtain the desired reliability the equipment utilizes standard components derated as required. Whereas this method provides assurance for continued operation under the stress of field conditions it also provides the possibility of higher powered performance under stable or "on-site" conditions. Stringent size requirements were dictated by limited availability of vehicular space; specifications called also for rapid tuning across the band to be covered. These varying needs have been satisfactorily met in the design of this equipment.

Three transmitter power amplifier heads are used in the equipment to cover a broad frequency range, each rf head covering a range of approximately one octave in the UHF frequency range. Each power amplifier employs two ML-7211 tubes in the two stages of amplification; power output is 30 to 40 watts. To facilitate ease of maintenance all units are "slide-in/plug-in" to thereby eliminate cabling as well as providing quick field service.

Design Development

Prior to the establishment of the final transmitter design (quarter-wave cavity amplifier using planar triodes), several other methods were considered. Among these was a strip line cavity using a miniature tetrode. Mechanical complexities, problems associated with adequate bandwidth (as related to high capacitance in the tube) and screen bypassing prompted consideration of the planar triode-coaxial cavity combination. The triodes proved easier to tune, required simpler contact assemblies and had gain and efficiency equal

A Multi-Channel Radio Relay for Tactical Use

As told to Cathode Press by N. F. HAMILTON-PIERCY, Development Engineer
Telecommunications Department, Commercial Products Division
Canadian Marconi Company

to or better than that of the tetrodes. It was at this point that the planar triode, ML-7211, was chosen over the ML-7289 triode, the former tube offering considerably higher power under either full or derated power operation.

Use of coaxial quater-wave resonators or cavities was established after experimental results had shown that other devices, notably the variable inductance tuner, did not offer the long term reliability required. Three resonators were designed, one for each rf band to be covered. Of unusual interest is the folded quarter-wave cavity used with the lowest frequency band, Band I. See Figure 1.

Amplifier Design — Band I

The size limitations imposed on the Band I amplifier section of the radio relay provided a most interesting design challenge. Using the planar triode ML-7211 with a plate capacitance of 2.3 pf and with no further capacitance loading, it was apparent that the resonator would have been too long to be accommodated within the required 10 inches of length. By increasing the characteristic impedance to a very high value or by further capacity loading, the required short length could be achieved, but both bandwidth and efficiency would have suffered; also the cross sectional dimensions would have been excessive. The method adopted was to use a folded or re-entrant resonator in the plate circuit. The physical design was established such that the mean cavity length very closely approximates the electrical length. In Figure 2, the re-entrant configuration is compared to the standard configuration. It will be noted that the capacity probe used for the output coupling is normally found in the plate line. Here, however, it was necessary to incorporate the movable probe in the grid line. This presents no problem since the tube operates in a grounded-grid circuit.

The plate resonator was constructed with a characteristic impedance of about 38 ohms and the cathode resonator with an impedance of about 53 ohms. These impedances were determined after considering mechanical size and the provision of a large ratio of C_aZ_{oa} to C_kZ_{ok} for stability. The capacitive losses were kept to a minimum by designing around this order of impedance.

Using conventional triode amplifier theory it can be seen that a load between 1000 and 2000 ohms satisfies the requirement for a power output in excess of 30 watts from a 600 volt supply, with the tube operating at approximately 50% efficiency. Using the highest load value:

$$Q_L = \frac{R_L\,(\Theta + \sin\Theta\,\cos\Theta)}{2\,Z_o\,\sin^2\Theta}$$

where $R_L = 2K$ ohms

$$\tan\Theta = \frac{1}{\omega\,C\,Z_o} \quad \text{where } C = 2.3 \text{ pf for the ML-7211}$$

$Z_o = 38$ ohms

A 3 db bandwidth is obtained with a Q_L of 42 to 43. By increasing coupling at the lower frequency portion of the rf band the bandwidth may be kept relatively constant over the entire band.

Re-entrant plate cavity dimensions were determined by first equating the total length of the cavity for a 2.3 pf loading capacitor and a 38 ohms impedance, then determining the portion needed to tune over the required band. The remainder of the cavity is then folded back such that its mean geometric length is equal to that portion of the basic cavity from the upper band tuning point to the tube grid-plate space. Care has been taken to insure that the 38 ohms impedance is maintained as far as possible. Plate dc isolation and rf bypass is maintained by a thin mica spacer. Figure 3 illustrates the power amplifier schematic diagram for Band I.

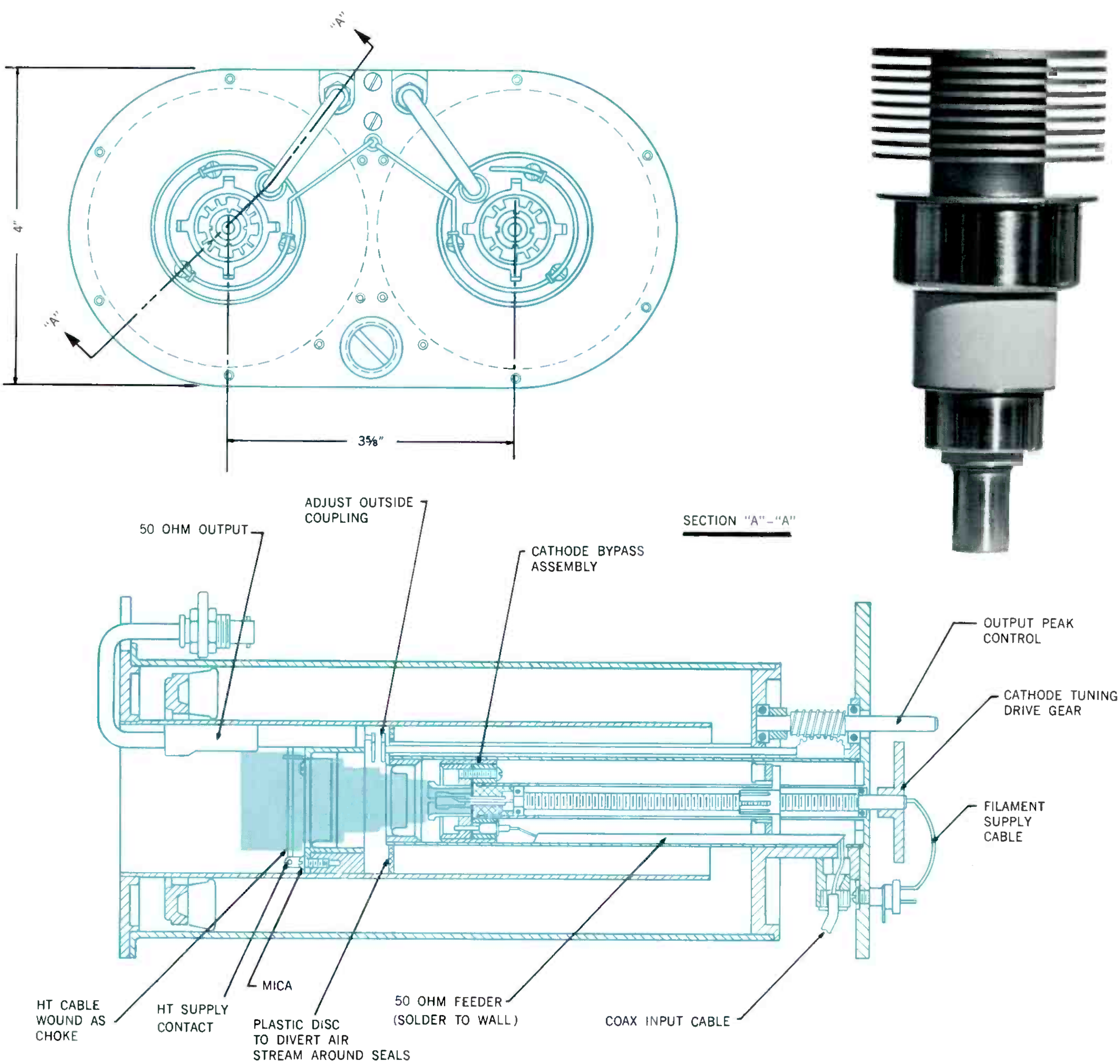
The driver amplifier and output amplifier can be made mechanically identical, the only difference being the choice of the dc operating point. This gives a convenient arrangement for gang tuning and the plate resonators can share a common drive screw. However, the output matching conditions are different and individual drives are required for the output probes.

Cathode Circuit

The cathode line of the cavity is conventional, heavily loaded with capacitance and consists of a brass cylinder within a teflon cylinder. By this means the insulation, dielectric, and support for the de-coupling capacitors are built into the cathode assembly, itself consisting of three ceramic feed-throughs. Ac input to the cathode, dc cathode bias and one side of the heater supply are taken by a coaxial lead soldered to the face of the grid cavity and, by direct connection, terminated by the cathode. A low pass filter isolates the input signal from cathode dc and ac voltages. Heater voltage to the cathode is obtained from a well stabilized 5.5 volt source. (The 5.5 volt figure was established after extensive experience with operation of the 3CX100A5 tube and is chosen for maximum life in operation; all other tube operating voltages are obtained from this same source.)

The cathode supply circuit is driven by a dc amplifier

Figure 1 — Quarter-wave re-entrant cavity for Band I transmitter.



which is, in effect, a constant current series source. This provision is made to limit the driver amplifier output to prevent overdriving of the output stage and to protect the amplifier tube grids. In addition, the constant cathode current maintains a constant G_m and good match. Figure 4 shows a schematic view of the constant current regulator.

Cathode self bias is used and the dc is supplied via the signal input lead. As mentioned previously, a large amount of capacity loading is used such that the resonator length remains short and a large $C_k Z_{ok}$ value is maintained.

Amplifier Performance

Measurements of the Band I amplifier show that gains up to 11.3 db can be achieved across the band with power output in excess of 30 watts. Indeed, power as high as 50 watts could be reached with 9.6 db gain when all circuits were aligned, the efficiency being greater than 50% under these conditions. Bandwidths in general were between the two theoretical values although a slight loss of gain was noticed when the probes were set for bandwidth considerations rather than for maximum power output.

The amplifier run as a driver gave gains in the order of 17 db with an efficiency around 33% and an output of 9 watts. The driver input match was very dependent on plate current, and for a good match the minimum current was in the order of 50 mA, the match being between 1.8 and 1.2 VSWR across the band. Stability of match was enhanced by use of the constant current dc cathode feed previously described. Transmitter performance characteristics are summarized in Figures 5a, 5b, 5c, 5d and 5e.

Mechanical Considerations

Cooling: Because of the construction of the re-entrant portion of the cavity, the tube plate radiator is obscured. Since space between the end of the amplifier and the back face of the transmitter box is not large, a special ducting was devised. With an air flow of about 15 cubic feet per minute (well in excess of that normally required to dissipate the anode heat) the hottest point around the anode does not exceed 180°C under any operating condition. A small portion of the air is taken through spaced voids in the spring fingers and passes over the grid and cathode seals.

Ambient air temperature conditions over which the proper cavity/tube temperatures should be maintained range from plus 75°C to minus 45°C. Maximum altitude for operation is 10,000 feet.

General: The cavity is made from aluminum. It is finished with a copper flash over a zinc base, the copper being heavily plated with gold. The gold is very durable, resists corrosion and provides a good contact surface for the spring fingers.

The spring finger sockets employ chamfered cathode contact entry points and provide good centering for the tube and are of very durable construction. The overall shape of the contact fingers is conical.

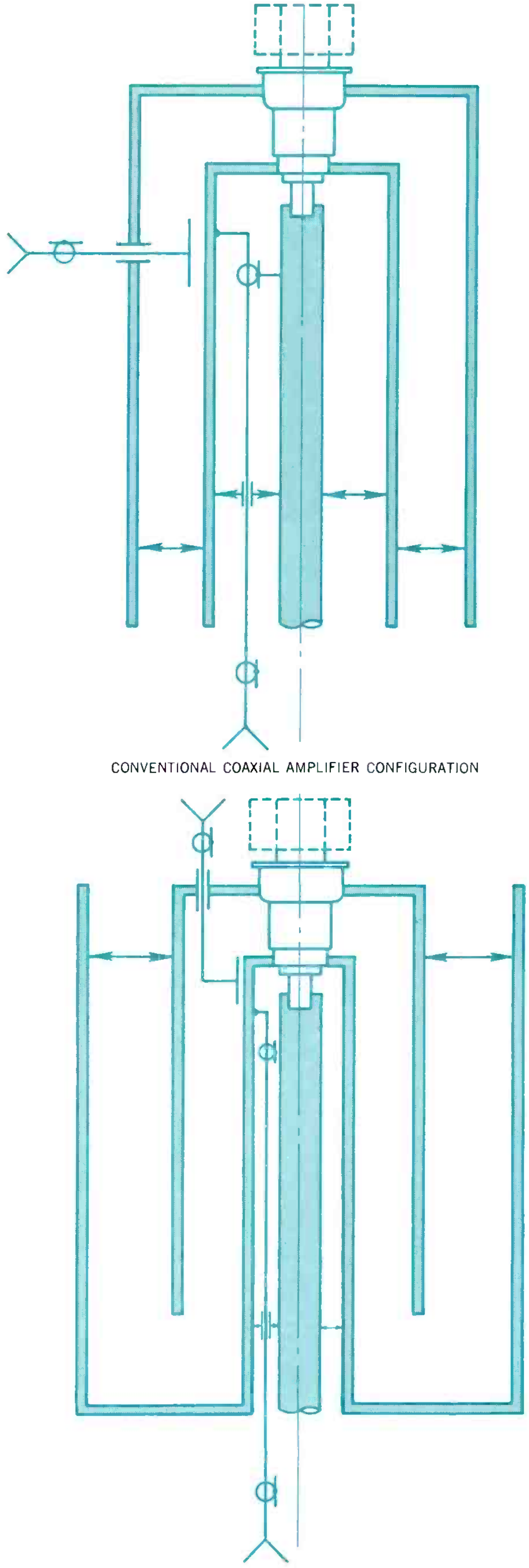


Figure 2 — Comparison of normal and re-entrant amplifier designs.

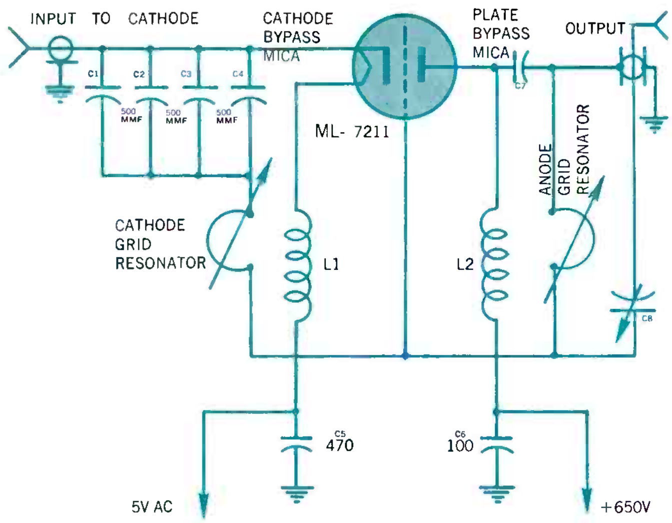


Figure 3 — Band I power amplifier schematic design.

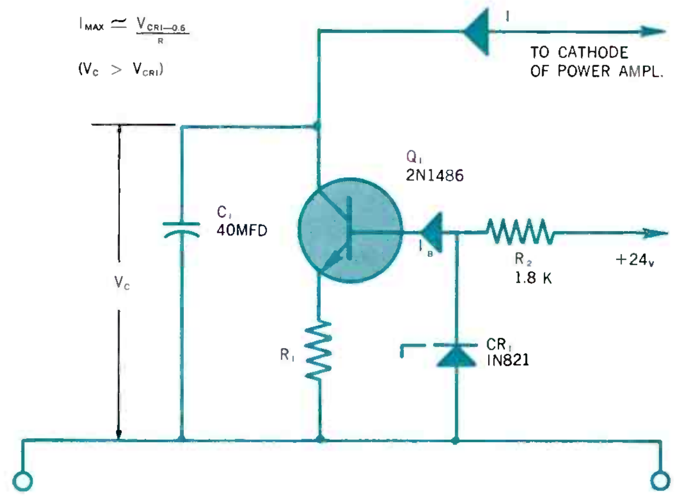


Figure 4 — Constant current regulator.

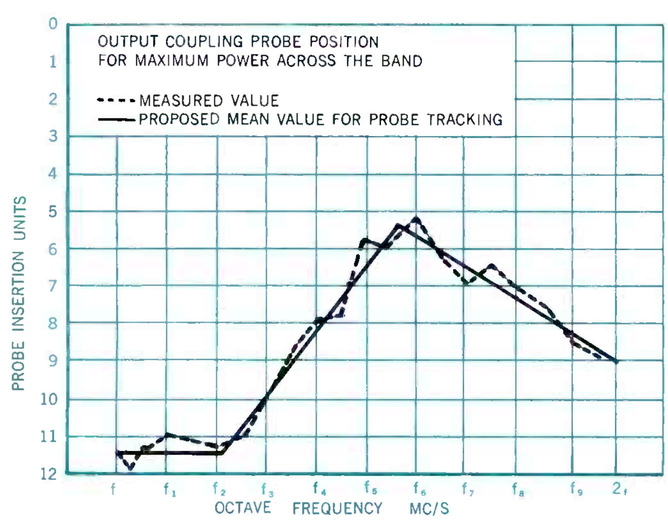


Figure 5a — Band I amplifier probe tracking the maximum excursion of the probe represents a movement of 1/32″ using a profiled cam.

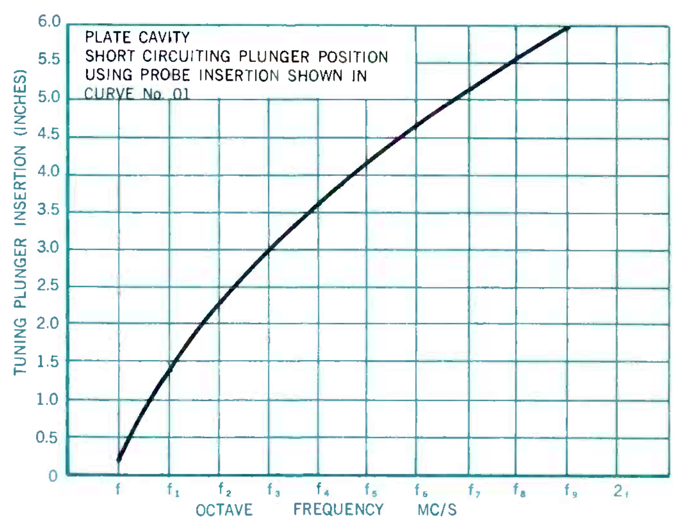


Figure 5b — Band I amplifier tuning plot follows a nearly linear curve.

Amplifier Design

High Frequency Bands: Amplifiers for Bands II and III use a conventional/nonre-entrant cavity design employing a grounded-grid configuration, direct coupled input to the cathode and capacity probe output. The ML-7211 planar triode is employed in both amplifiers. The performance of both amplifiers is similar to that obtained for the Band I unit, except that the gain is slightly reduced at the high end of Band III and that the input match of the Band III amplifier requires a ¼ wave resonator tapped to act as a transformer.

The usual practices of a large ratio of C_aZ_{oa} to C_kZ_{ok} for stability in the two tank circuits are followed. The plate circuit is designed for a high unloaded "Q" for maximum rf efficiency. The impedance of the circuit is 55 ohms with the outside tube diameter a maximum for the available space.

The cathode circuit and dc operating points for driver and output stages are essentially the same as for the Band I unit. Cooling of the tubes is simplified by the cavity construction.

Conclusion: The three amplifiers meet all requirements of power, bandwidth and size. Their efficiency is reasonably high for a triode amplifier at these frequencies. Life and general reliability should be good as care has been taken to operate the planar triodes conservatively and overall construction is rugged.

Considerations in the Choice of the ML-7211

In the design of these amplifiers, an evaluation program including both study and experimental test was undertaken

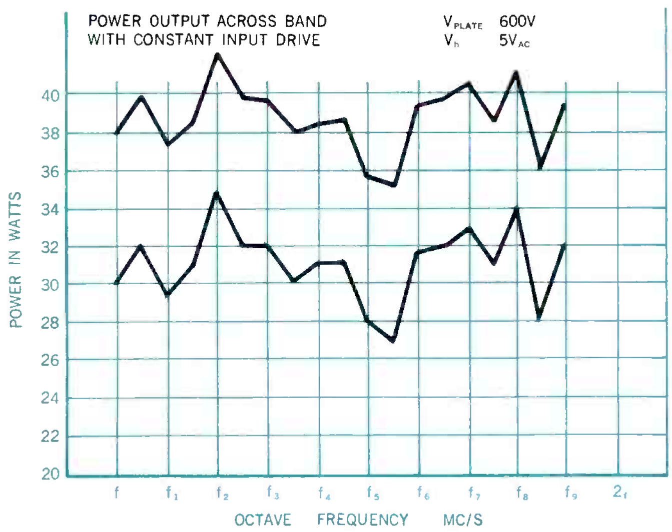


Figure 5c — Power output across the band and Band I amplifier.

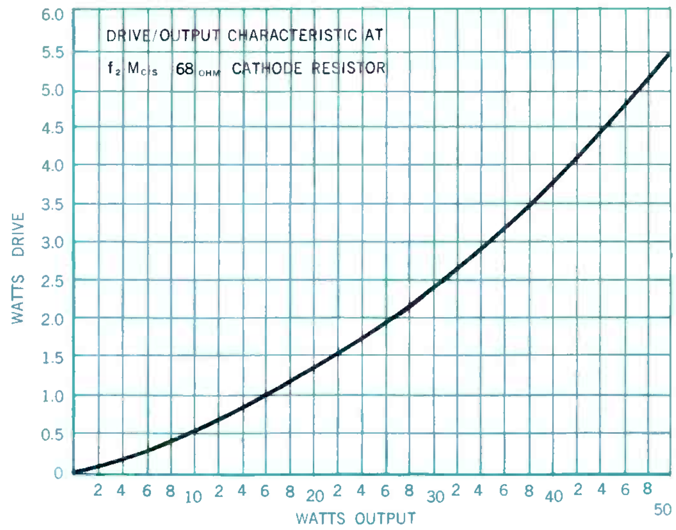


Figure 5d — Drive vs. output at lower end of Band I.

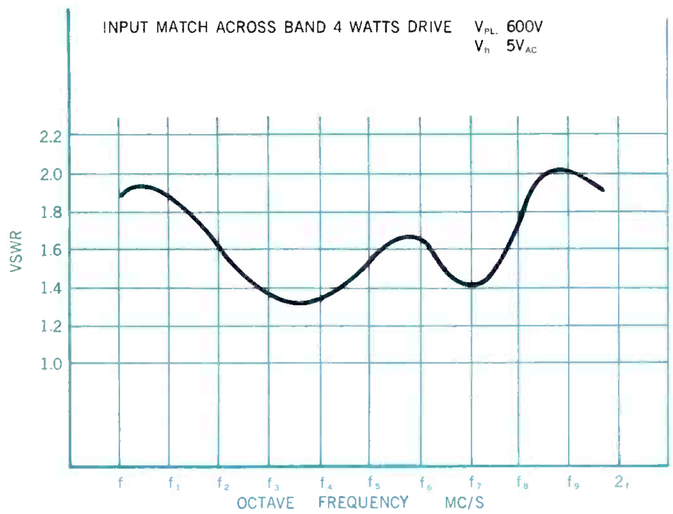


Figure 5e — Input match across Band I.

to determine the type of tube to be employed. This program indicated the use of the ML-7211 tube, for the following reasons —

1. With the 7211 tube, power output meeting equipment requirements with adequate margin can be achieved under conservative operating conditions.

2. The 7211 tube offers good power output in relation to the volume of the tube, permitting relatively compact assemblies.

3. Experience with this and previous tubes of the same family shows that reliable long life performance can be achieved.

4. In the UHF frequency range, the 7211 offers gain and efficiency comparable with the best offered by any other tubes commercially available at this time.

5. The construction of the 7211 meets the requirements for ruggedness imposed by the application of the equipment to mobile tactical use.

6. The 7211 exhibits good uniformity from tube to tube, providing ease of replacement in the field.

7. The input impedance of the cathode is suitable for simple direct coupling.

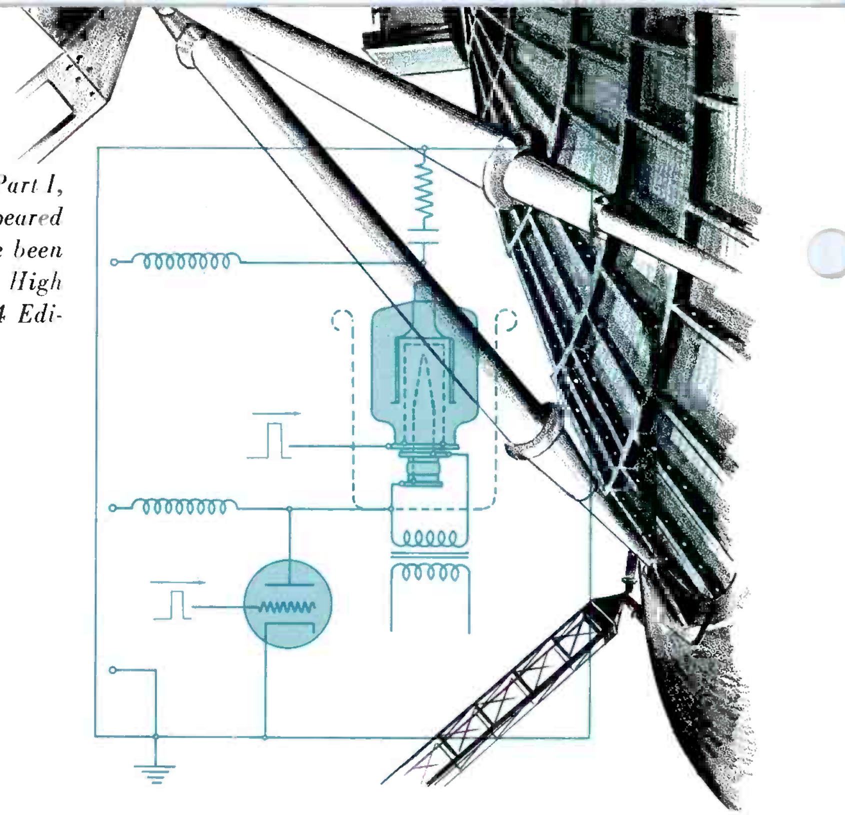
8. In the event of field emergency, a 7211 tube may be replaced directly by other tubes of the same family such as the 3CX100A5 or 2C39. In this case, some loss of gain and reduction of output must be expected, but the equipment can be kept in operation.

Summary

A description has been given of the design of power amplifiers for use in a UHF radio relay equipment designed for mobile tactical applications. Considerations of high reliability, reduction in space occupied, and exceptionally wide tuning range, have greatly influenced the design. In particular, a re-entrant cavity design is described which was designed to meet requirements of limited cavity length in the lower frequency ranges of the equipment. Careful consideration of a variety of tube types led to the selection of the 7211 triode used in a grounded grid configuration for this service.

Editor's Note:

This is Part II of a two-part article on this subject. Part I, "Design, Theory, and Operational Characteristics" appeared in CATHODE PRESS, Vol. 21, No. 1. Both parts have been reprinted in Machlett's brochure of "Pulse Tubes for High Voltage, High Power Video and RF Pulsing" (1964 Edition).



Interactions Between Pulse Modulator Tubes

In the previous sections the discussion has centered on tube design parameters and the variations in characteristics by tube type. In the present section the phenomena of tube behavior in various circuit situations will be discussed.

1. Pulse Width, Pulse Repetition Rate and Pulse Rise Time.

In tubes with thoriated-tungsten cathodes the maximum pulse width is not limited by the emitter itself. Usually the control grid temperature is the limiting factor. In the case of tetrodes the screen-grid temperature is usually the limiting factor. The tube data sheet gives both a maximum pulse width and a maximum average grid dissipation. It is reasonable to assume that wider pulses could be used if the peak power were reduced accordingly. Peak grid dissipation is the product of the peak positive grid voltages with respect to the cathode multiplied by the peak grid conduction current. Equation (7) shows that the product of the pulse width by the peak power is a constant for a fixed grid temperature rise. If the rate of diffusion of heat from the wire surface into the volume of the wire is taken into account, $p_g \propto \tau^{1/2}$ is a constant limited by maximum permissible surface grid temperature. This relation permits an approximate extrapolation between peak power in the grid and pulse length, i.e., if a tube has a typical rating giving e_g, i_g, and τ max, the peak grid dissipation can be increased for shorter pulse widths according to the above relation. Of course the average grid dissipation cannot be exceeded.

Only electron conduction currents to the various tube electrodes can give rise to electrode dissipation. Capacitance charging currents in the effective tube input capacitance do not result in any control grid dissipation. For this reason grid dissipation is not affected by wide variations in the pulse recurrence frequency at constant duty. If the screen grid voltage is kept constant, the dissipation in this grid is independent of pulse width and repetition rate and is simply E_{sg} x I_{sg}, where I_{sg} is the average screen-grid current. If a tetrode is operated close to or below the knee of the plate current curves on the constant grid drive characteristic curves, the screen-grid current may increase substantially and E_{sg} may not be constant during a pulse. A graphical integration of $e_{sg} \times i_{sg}$ for a single pulse may be used to determine the screen dissipation.

When short pulses are used, the repetition rates may be high. Although high repetition rates do not affect the manner of calculating grid dissipations, they do make a great difference as regards anode dissipation. In this case it is possible to do a graphical integration of i_p x e_p as for screen grid case above. To do so would require a detailed calculation from the load line on the characteristic curves. Fortunately there is a much simpler method which may be used. The output capacitance of the tube together with any circuit capacitance between plate and cathode must be charged or discharged by the amplitude of the output voltage pulse. Since these capacitance currents must be furnished by conduction current through the tube, and since the tube resistance is large compared with other resistance in the charging circuit, nearly all these charging or discharging losses will show up as anode dissipation. Since this energy is put into

Vacuum Power Tubes For Pulse Modulation

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Manager Technology,
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Part 2

and Circuits

the anode on every pulse, the plate dissipation P_d now becomes,

$$P_d = e_p \times i_p + \frac{1}{2} C_{out} (E_{bb}^2 - e_p^2) \times p_{rr} \qquad (15)$$

Here e_p and i_p refer to the instantaneous tube drop and plate current during the flat top of the pulse, C_{out} is the total stray capacitance which is discharged (or charged), and p_{rr} is the pulse repetition rate. For very high pulse repetition rates, the term $e_p \times i_p$ may become negligible. When that happens the efficiency of the switching operation is low. Dolan[15] has discussed this subject in more detail.

In floating deck type modulators used to switch modulating anodes of klystrons, the capacitance charging current usually exceeds the resistive component of the load current. Swanson[16] has discussed tube ratings for such cases. It should be noted that the average plate dissipation depends only on $1/2\ C\ V^2 \times p_{rr}$ and is not affected by the rise time of the pulse. Of course the peak anode dissipation is dependent on the rise time.

The added losses due to charging or discharging stray capacitance is not peculiar to vacuum tube modulators. Any time a capacitance is charged (except for inductance charging) the efficiency is fifty per cent. Any time a capacitor is discharged into a non-useful load, the energy is thrown away. Line type modulators cannot be matched into a capacitative load and tube plus stray circuit capacitance is discharged into a non-useful load. The P_b factor in hydrogen thyratrons is based on this reasoning. With a gas tube this energy may be partially dissipated in circuit resistance rather than in the tube itself. Unless it is accounted for, some components may be overheated.

For vacuum tubes with oxide cathodes, limits on pulse width and pulse repetition rates as determined by electrode dissipations are the same as for thoriated-tungsten tubes. However, the oxide cathode itself may put additional restrictions on the pulse length. It is well known that currents of 20 to 100 amperes per square centimeter are obtainable for microsecond pulses from oxide cathodes in magnetrons and that such high current densities cannot be maintained for pulses greater than a few microseconds. The situation in oxide cathode pulse tubes is quite different. It has been shown in equation (5) that space charge in the outer grid to anode spacing limits cathode emission in practical tubes to a few amperes per square centimeter. Pulses of millisecond duration are satisfactory at such low peak current densities. However, as noted in the section on oxide cathodes, it is essential that the tube be monitored in production at the maximum pulse width for which it is rated and used.

Excessive average electrode dissipation or high envelope temperature may lead to an increase in the gas level of a tube which in turn may cause cathode deterioration. If the gas reacts chemically with the cathode, the pulse current will decrease during the pulse. If the released gas is hydrogen, and the pressure is high enough, it will ionize and reduce the space charge either at the cathode or between screen grid and anode. The net result may be an increase in pulse current during the pulse. Since positive ions move much slower than electrons, it may take a time of the order of microseconds before the effect becomes apparent.

If short pulse rise time is required, the cathode must be capable of providing the necessary peak current to charge the stray capacitance. This current may be considerably greater than the load current. For this application, the oxide cathode has an advantage over thoriated tungsten, since by applying additional drive it is feasible to obtain high currents for fractional microsecond pulses during the time when e_b is high.

2. Grid Drive Requirements and Gain.

An analysis of grid drive requirements for receiving tube pulsed applications has been given by Neeteson[17]. The same general approach may be used with modifications for power switches. It is not the intention here to write an equation for the input pulse in terms of various circuit constants of the input and output circuits, but merely to point out the salient features. If the capacitative currents in both the input and output circuits are small compared with the pure resistance currents, then the output load line of Appendix III will be a straight line. The grid current will increase as the plate voltage falls. Figure 15 shows the instantaneous grid current, i_g, as a function of the instantaneous grid voltage, e_g, for various fixed plate voltages for the 7560 tube. A load line for the input circuit is shown assuming that the open circuit grid drive voltage is e_{g1}. The slope of this line is determined by R_d, the internal resistance of the driver. The effective total drive is $e_{g1} - i_{go} \times R_d$, where i_{go} is the grid current at the operating point. If the output load has a parallel capacitor such that the capacitative charging current is larger than the pure resistive load current, then the load line of Appendix III will change to that shown in Figure 16, E_{bb} — Op. The exact form of this curve will depend on the circuit parameters and the available emission from the tube. Similarly, the fall of the pulse will be determined by the value of an effective RC time constant. Since on the pulse rise the grid of the modulator tube is positive and the tube plate resistance is low, the time constant is considerably smaller than on the pulse fall. In the latter case the modulator tube is open circuited. The capacitance of the tube input circuit has a similar effect on the rate of rise and fall of the driving pulse. If the time constant of the output circuit is greater than that of the input circuit, the drive pulse will have a faster rise time, since the grid conduction current is lower at the higher plate voltages. If the fall time of the grid pulse is slow, it will cause an increase in the fall time of the plate pulse. This is so because the tube will not be cut off due to the slow fall of e_g. Furthermore, whatever plate current flows during this time will cause increased plate dissipation. This type of operation can be used advantageously to avoid a fast interruption of plate current, particularly during a fault condition.

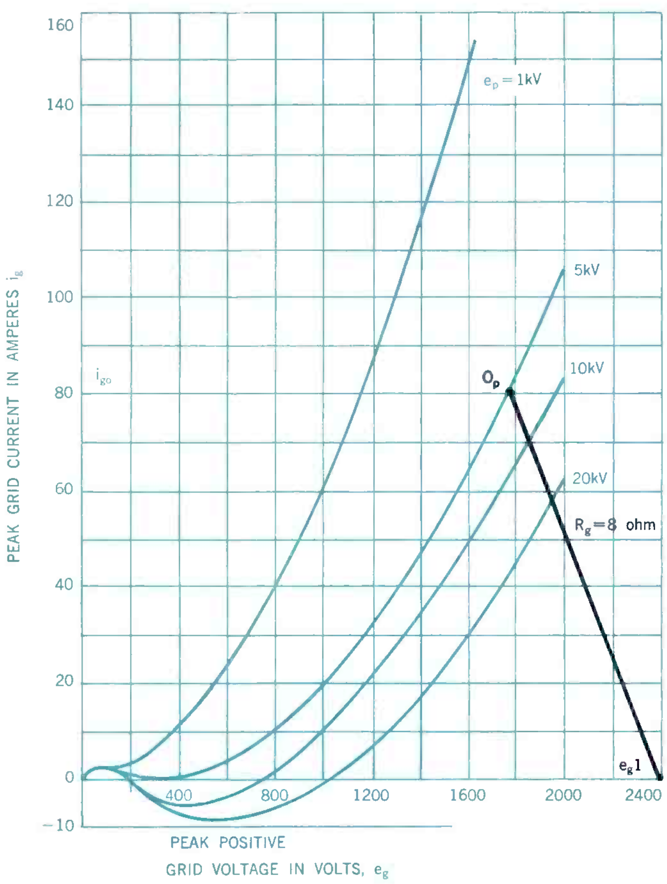

Figure 15 — Input characteristic of ML-7560. Instantaneous Grid Current versus Grid Voltage with Plate Voltage e_p as a parameter.

It is generally assumed that the higher amplification factor of the tube the greater will be the voltage gain. To obtain a figure for voltage gain it is only necessary to determine the operating point on the characteristic curves and to determine the proper cutoff bias, E_{cC}. The voltage gain, A, will be given by

$$A = \frac{E_{bb} - e_p}{e_g + E_{cC}} \qquad (17)$$

We can obtain an approximate formula for voltage gain in terms of the amplification factor by using equation 10b and taking the output voltage, E_o as $i_p \times Rl$. The total drive voltage will be $e_g + \frac{E_{sg}}{\mu_{sg}} + \frac{e_p}{\mu_p}$, and $\frac{E_{bb}}{\mu} = -E_{cC}$.

Rearranging the above results, the following equation for the voltage gain is obtained,

$$A = \frac{E_o}{E_i} \approx \frac{1}{\frac{1}{c\,Rl} + \frac{1}{\mu}}$$

If μ is much larger than c Rl, the formula simplifies to

$$A \approx c\,Rl$$

For example, the μ of a gun type modulator may be practically infinite and only a small cutoff bias is required. If the gun type tube has a relatively low perveance, the voltage gain is usually about the same as for conventional triodes. This figure for voltage gain is the same as that to be used in calculating the effective input capacitance in equation (8). It is apparent that the actual voltage gain has nothing whatever to do with μ unless μ is low enough to require a bias voltage to be used, and then it gives the contribution to total drive by telling how much of the drive is required to overcome the negative grid bias. The voltage gain for triodes is of the order of 10-20, and for tetrodes from 20 to 40. In order to determine the power gain it is necessary to multiply the voltage gain by the current gain. The current gain is obtained by the ratio of i_p/i_g at the chosen operating point. For very low μ triodes, shielded-grid triodes, beamed triode guns and tetrodes, the current gain may be from 10 to 50. For conventional triodes, the current gain will be 3 or 5. The produce of these numbers give power gains of 30 to 100 for triodes and 200 to 2000 for tetrodes or beamed structures. Practical power gains are less than these factors, particularly for the higher gain tubes. It is essential to use a resistor in parallel with the tube input in order to improve stability and reliability. If the control grid current is nearly zero, as in the case of high gain tubes, any parallel input resistor at all substantially reduces gain. Of course, the higher the stage gain, the stiffer are the requirements on driver pulse shape, amplitude control and stray pick-up. It is difficult to set up high power stages with fixed circuitry. Adjustments must be made to accommodate tube variations. This problem is particularly important for tubes with oxide cathodes. The life performance of an oxide cathode tube is simply a matter of how much cathode deterioration one can live with. As the cathode bulk resistance slowly increases, the time arrives when one has to replace the tube, raise the drive power or be satisfied with reduced output. The emission holds up in thoriated-tungsten tubes until decarburization of the cathode wire is complete, then emission drops sharply.

3. Some Causes of Circuit Instabilities.

Secondary electron emission from grids or anodes can lead to pulse instabilities. The most common problem in triodes is where secondary grid emission causes a negative grid current area on the characteristic curves. Appendix III shows the region as it appears on the constant plate and grid current characteristic curves for the 6696 tube. Since high power communications transmitters use tuned circuits and follow an essentially resistive load line, the secondary emission area is not too troublesome. Some tube data sheets do not bother to show it. If one uses a load line such as is shown in Appendix III, it could give trouble either in pulsers or radio frequency amplifiers working with a reactive load. The easiest way to overcome this problem in an existing tube is to use a swamping resistor of such magnitude that the combined tube grid current plus resistor current is never negative or only slightly so.

In order to provide a constant amplitude pulse of long duration, it is common to select the operating point at a rather high tube drop. Discharge of the coupling condenser during the pulse would introduce droop. The output pulse may be kept constant in amplitude by increasing the grid

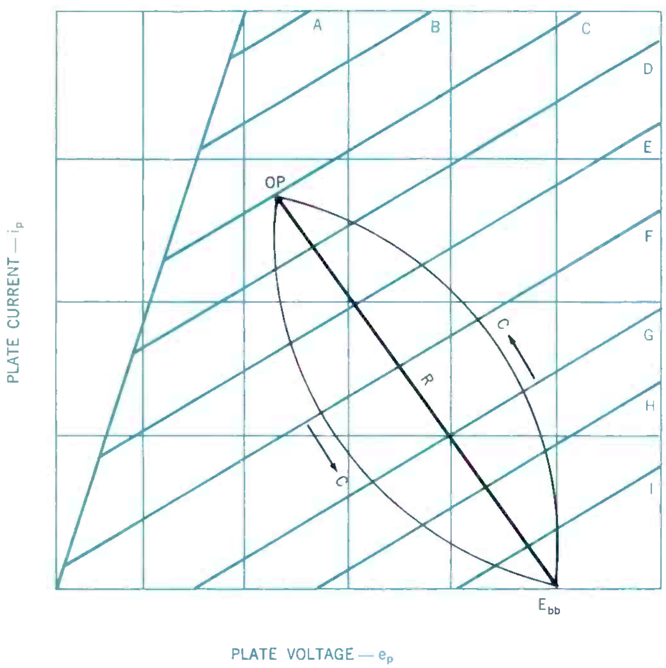

Figure 16 — Resistive and capacitative load lines on constant grid voltage characteristic curves.

drive during the pulse such that the operating point on the characteristic curve shifts at the end of the pulse to a lower value of tube drop. In this way the output voltage pulse may be kept at constant amplitude. At the beginning of the pulse the load line may cross the negative grid current area, depending on how high an E_{bb} is chosen to make up for the increasing voltage drop in coupling condenser voltage during the pulse. If the load line passes through the negative grid current area, the drive voltage is not controlled by the driver and the resulting effects will depend on tube and circuit interaction. In general it is not possible to achieve stable operation in this area unless the rise time of the pulse is so short that the total negative charge removed from the grid by secondary emission is small enough not to affect the driving voltage.

Another type of instability in pulse amplitude is due to space charge neutralization by positive ions. This subject has been investigated by Hernqvist[18, 19]. It occurs in tetrodes, shielded-grid triodes and other multi-grid tubes, if the residual gas pressure in the tube is not low enough. When the peak pulse current has been established in the screen-grid anode region, there is a potential dip in this region due to the space charge. The electron current ionizes the residual gas, and the positively charged ions will collect in this negative potential well. These positive ions neutralize some of the negative space charge, which results in a more positive potential gradient at the grids. The net result is an increase in plate current and decrease in screen-grid current. In other words, the plate current is no longer limited to the value given in equation (5) since this equation assumes that only electrons are present in the grid-anode region. For short pulses this effect is not noticeable because of the slow mobility of the positive ions. In general the time of formation may vary from a half to several microseconds. The lower the plate tube drop at the operating point, the deeper the potential well becomes and the more likely one is to see this effect. Even if the resulting small step in the pulse is not objectionable, it is not apt to be stable for long periods of time. It can also produce parasitic oscillations. See Figure 17.

4. High Voltage Breakdown and Circuit Problems.

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. For example, with proper circuitry the ML-7560 running at its maximum rated 50 KV dc plate voltage and pulsing a klystron load will kick out so infrequently, i.e., once in many hundred hours, that it is difficult to tell whether the tube itself caused the kick out. This tube will operate quite stably for hours in oil at 65 KV dc, but the kick out rate has not been determined under such conditions.

The study of high vacuum insulation has been the subject of a great many papers[6, 20, 21, 22] 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[23, 24, 25] 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 pulsers 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.

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

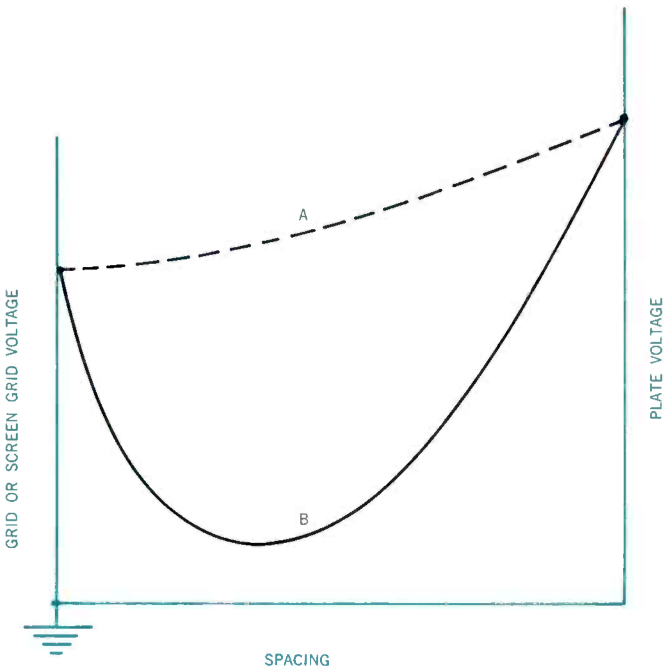

Figure 17 — Potential distribution between outer grid and anode; "A" for electrons in high vacuum, "B" for gas ionization neutralizing electron space charge.

necessary to have adequate spacing between these two surfaces, and the surfaces must be clean and smooth. Kilpatrick[6] has given a data for the maximum "spark free" potential differences between two electrodes in vacuum as a function of their spacing (Appendix II.) 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[6, 20, 21, 22] 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. It was pointed out in the beginning of this article that determining the proper spacing between the outer grid and anode involves a compromise between tube efficiency or size and an ultra-conservative maximum plate voltage rating. See Figure 3 and equation (5). It is easily seen from equation (5) that as d is increased e_p must also be increased if e_g 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.

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 tail, 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 (Appendix III) 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. See horizontal dotted line in (Appendix III). 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 voltages 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 18, 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.

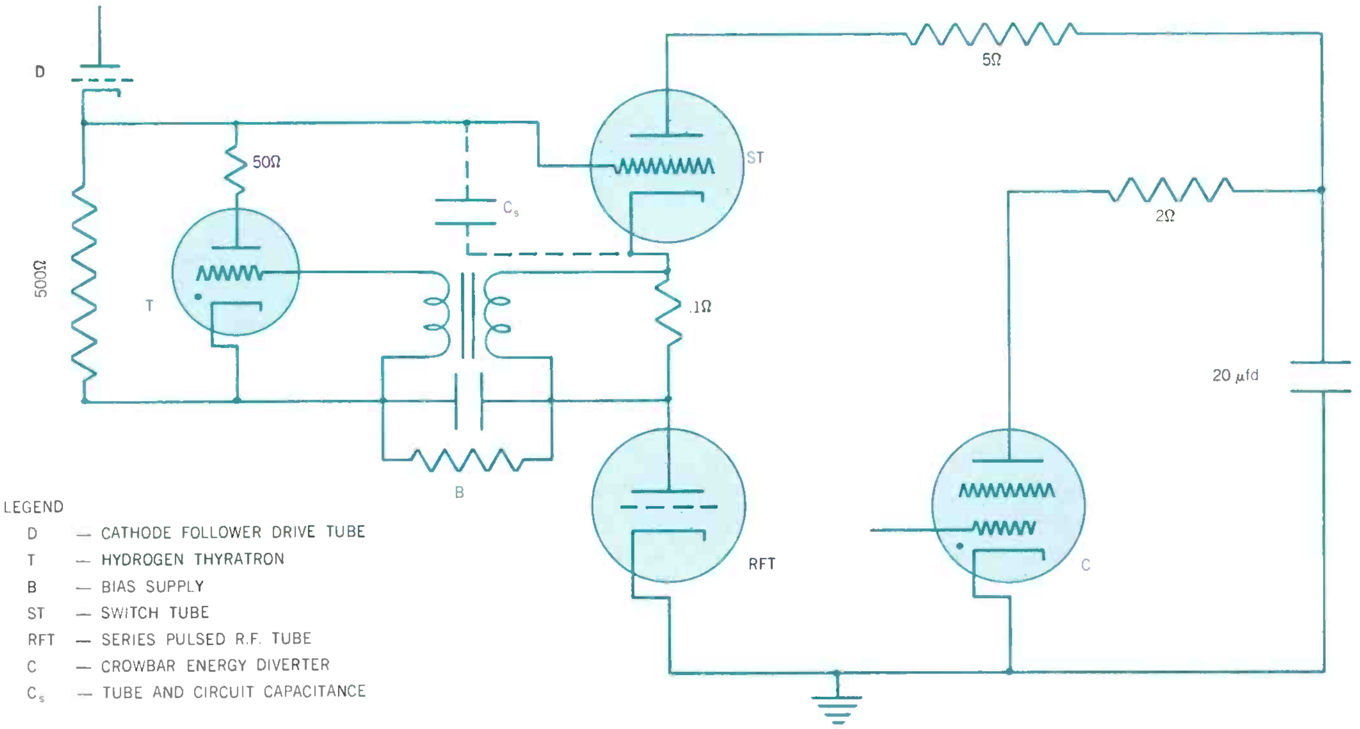

Figure 18 — Circuit showing a thyratron in a switch tube grid circuit. The switch tube is cut off when load tube arcs by firing the thyratron, T, by a voltage developed across 0.1 ohm resistor.

Barkenhausen-Kurz[26] 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 19 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 grid voltage of 1000 volts cannot arrive at the plate but ends up on the screen grid or control grid. Equation (5) 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.

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 re-

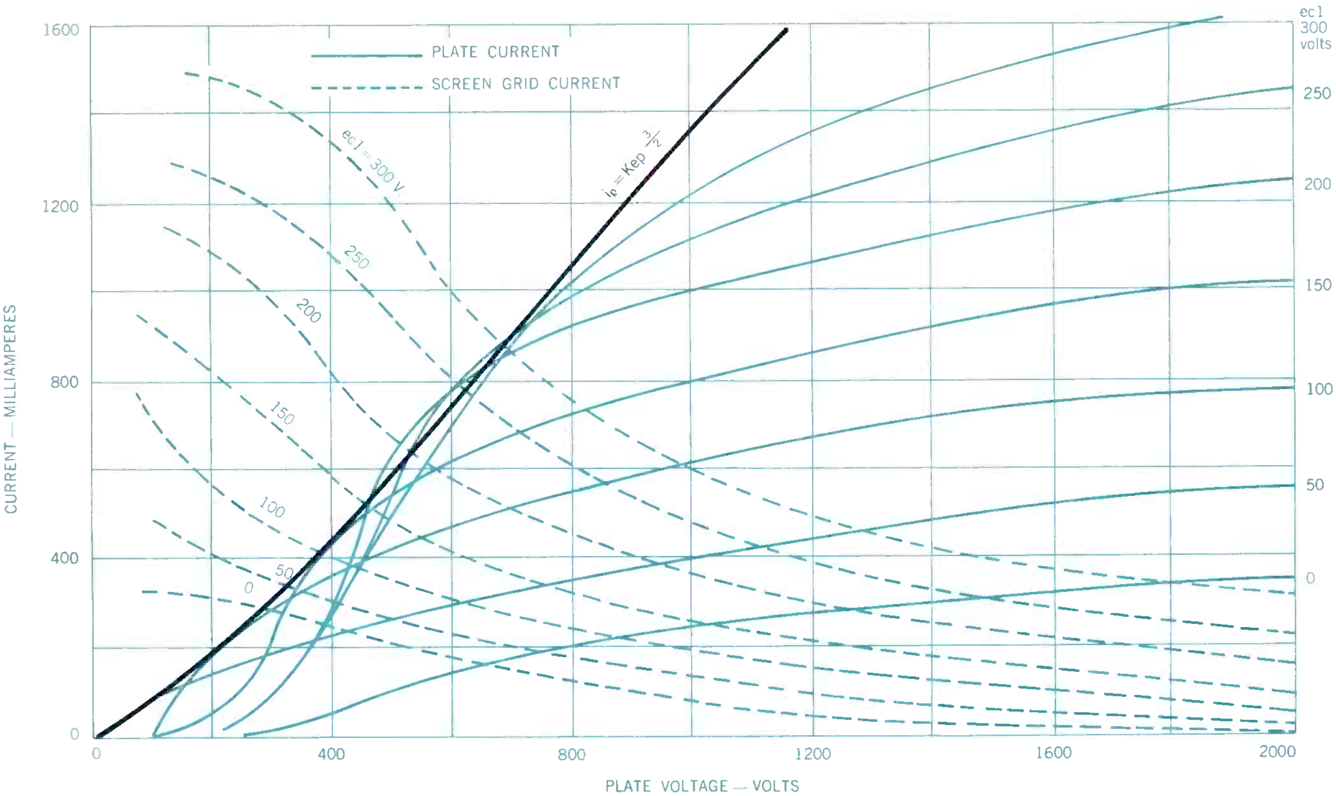

Figure 19 — Typical Constant Grid Voltage Characteristics for tetrode ML-7248. Line labeled $i_p = k e_p^{3/2}$ shows plate current drawn from virtual cathode between screen grid and plate (Equation 6).

sistance 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[23, 24, 25] to divert the stored energy in the circuit from discharging through the power or switch tube. It is also necessary to use 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.

5. Voltage Breakdown Outside of the Tube.

In the early days of pulse modulator equipment design, it was discovered that many radiation cooled tubes with long glass envelopes could withstand plate voltages several times the dc ratings given for CW oscillator or amplifier operation. Of course the peak plate voltage rating on all tubes used for CW rf applications is twice the dc power supply value, and therefore power tubes can be operated as pulse switch tubes at twice the dc ratings given for Class C rf oscillator or amplifier applications. The ratings for plate modulated rf power tubes are such that the peak of the rf voltage is nearly four times the dc plate voltage rating. It is usually reasonable to assume that the peak plate voltage due to backswing in pulse modulator applications can equal the peak rf plate voltage which would be encountered in case of rf applications with plate modulation. In this case the dc modulator tube rating would be about three and one-half times the dc plate voltage for the plate-modulated rf application. Although some of the older style radiation cooled tubes when used as switch tubes ran a factor of two higher than $3\frac{1}{2}$ times the dc plate modulated ratings, the same result is usually not possible with external copper anode power tubes because in the latter case the glass envelope is not long enough even if the internal vacuum spacing is adequate. Some power tubes, if immersed in oil, sulpher-hexafluoride or pressurized air, can be run at plate voltages considerably higher than inferred from the above discussion. Operation of commercial tubes at such high values of plate voltage will necessitate some high voltage aging at 15 to 20 per cent above the desired operating level. Furthermore, the user of such tubes will have no assurance that the manufacturer will continue to make tubes which will work in his circuit, since the manufacturer may not be checking such a high voltage characteristic. The user should obtain a firm rating from the manufacturer to be sure that future tubes will continue to do the same job.

As can be seen from the above comments, ionization of the air outside the tube limits the maximum usable plate voltage. Such ionization will lead to arcing over the tube envelope with danger of puncturing the glass or ceramic envelope. Conversely, if a tube normally runs satisfactorily within its maximum ratings and occasionally arcs over externally, it is proof that the plate or grid voltage rating has been exceeded due to some voltage transient. It is mandatory to keep envelope insulation clean. Dirty air or a collection of electrically precipitated dust on the tube envelope will lower the hold-off capability of the tube by a factor of two or more. For economy of space and to simplify problems of cleanliness, it is advisable to use oil or enclosed gas insulation above the 50 kilovolt level.

For operation of tubes in air at voltages above 10 kilovolts, the use of corona rings suitably disposed can improve the maximum rating of the tube and also offer protection against catastrophic failures. Properly designed corona rings reduce the maximum electric field gradient in the air outside the tube. Without corona rings the maximum electric gradient usually occurs at the metal-insulator joint. The corona rings should be designed such that in the event of transient overvolting, the maximum gradient occurs at the surface of these rings and then the flashover should occur in the space between the rings instead of over the tube envelope. It has also been shown that a blower driving air over the envelope seems to remove ions as they form and thereby substantially improving voltage stability. "Corona rings" are also useful under oil to reduce the electric field at the envelope seals and the probability of envelope puncture.

6. Effects of Alternating Voltage Heating of the Cathode.

Most thoriated-tungsten cathodes are composed of wires. If these cathodes are heated by alternating current, an alternating magnetic field exists around the filament wires and extends into the grid-cathode space. It has been shown by Hardie[27] that this time-varying magnetic field has an influence on the characteristic curves, particularly at low grid-drive voltages when the electron velocity in the grid-cathode space is low. At full grid drive and maximum cathode current density, the effect is small. It may be necessary to use dc cathode heating if extremely flat-topped pulses are required. When dc cathode heating is used and long tube life is desired, it may be necessary to change polarity of the heater terminals every thousand hours or so. The advisability of changing polarity is determined by the ratio of average plate current to the filament heating current. If the average plate current is less than 1% of the filament heating current, it will not be necessary to change polarity. The problem here is due to the added heating on that end of the filament wire which carries the average plate current as well as filament heating current. The criterion of 1% says that the added wattage on this end of the wire is 2%. If this figure is allowed to go to a 5% increase in wattage, the emission life of these filament legs will be halved.

Another effect of alternating voltages on cathodes is the volt drop from one end of the cathode to the other. For all cathodes except those that are indirectly heated (radiation heated or bombarded cathodes), the effective grid-cathode driving voltage varies due to the difference in true grid driving voltage from one end of the cathode to the other. For example, if the rated heater voltage is ten volts and one side of the cathode is at ground potential, the grid voltage with respect to the grounded end of the cathode is simply e_g, the applied grid voltage. The driving voltage at the other end of the cathode will assume all voltages in the range of $e_g \pm 14.1$ volts in the course of one cycle of the heater voltage. If this much uncertainty in the grid drive voltage is critical in an application, then dc filament excitation may be required. A center tapped resistor across the filament terminals which draws about 5% of the normal cathode heating current will considerably reduce ripple due to this cause.

7. Application of Tubes in Parallel or Series.

Hard tube switches may be used at full ratings in either parallel or series operation, or both, but it is necessary to derate tubes on both voltage and current unless one is prepared to make rather extensive adjustments periodically and whenever tubes are changed. At a fixed grid drive and fixed tube drop (plate voltage), the plate current may vary from tube to tube by as much as 10% for tubes with thoriated-tungsten cathodes and even more for oxide cathode tubes due, in the latter case, to the slow deterioration of oxide cathodes during life. If two tubes are used in parallel and only total or average current is monitored, one tube may be running at excessive plate current. If tubes are operated close to or below the knee of the plate current curve on the constant grid drive characteristics, the situation may be considerably worse. When tubes are used in parallel, maximum cathode current and grid dissipation ratings should be reduced by 5 to 10%.

Tubes in parallel may find themselves opportunely situated to oscillate in a push-pull mode at some frequency determined by the circuits composed of plate leads, stray capacitances, etc. Usually a non-inductive resistor in individual grid and plate leads suffices to lower circuit Q's to a value which prevents oscillation. It is also possible to determine the critical circuits and adjust the feedback such that the phase of the fed-back energy is improper to support oscillations. Multiple-tube pulse modulators have proven much simpler as regards suppression of parasitic oscillations compared with rf amplifiers or oscillators.

When tubes are used in series, the primary problem is to see that plate voltage ratings are not exceeded. If one tube is switched on before the second tube, the full voltage will appear across the non-conducting tube. It is not necessary to have the rate of rise of the grid drives identical, since the voltages across the tubes need not be balanced, and any current through the load subtracts from the total instantaneous tube voltages. At the end of the pulse, the time constant for the plate circuits of the two individual tubes must be reasonably matched so that the voltage across either tube never exceeds the individual tube rating. Here again circuit details are much less critical if tubes are at 80 to 85 per cent of their maximum plate voltage ratings. Since tubes passing the same current in series will have different tube drops, depending on variations in characteristic curves and also variations in drive voltage, maximum grid and plate dissipations should be lowered by about 10 per cent. Exact values for derating should be worked out in each individual case, depending on the particular circuits used and the tolerances allowed on circuit elements and on voltage regulation.

In balancing voltages and time constants, it should be remembered that the capacitance data on tube data sheets are only the interelectrode capacitances considering that the tube is far removed from other circuit elements and the grounded cabinet walls. The tube manufacturer cannot give more detail since he does not know in what environmental conditions the tube may be situated. It is necessary to open conductive leads and measure actual capacitances with the tube in place.

One item which is often overlooked when operating tubes in series is due to the fact that electrostatic fields add. Consider two tubes connected in series as shown in Figure 20. Each tube has 50 kv from plate to cathode when both tubes are non-conducting. Nevertheless, tube A has capacitance to the grounded case and the difference of potential here is 100 kv. Under these conditions the electric field gradients at the glass-metal seals of tube A may be considerably greater than those of tube B. This situation may cause corona at the plate seal of tube A and may even increase the voltage gradient inside the vacuum envelope of tube A. The latter effect can happen if the electrostatic field due to the difference of plate voltage from the plate of tube A to ground reaches through the glass tube envelope to the internal tube electrodes. Such an effect is particularly likely with tubes using large glass bulbs and radiation cooled anodes. Tube A may be protected from such stray electrostatic fields by surrounding the cathode-grid structure with an electrostatic shield as indicated by the dotted lines in Figure 20.

In series operation of tubes particular care must be taken to keep lead inductance to an absolute minimum. Large diameter coaxial connections are advisable. Otherwise, very large transient voltages may build up due to lead inductance and high rates of change of current, particularly under fault conditions when extremely high di/dt can occur. Great long arcs will fly in all directions. For the same reason tubes with large internal cylindrical leads to all electrodes will be much freer of flash-arc damage than tubes with straps connected from tube terminals to the active electrodes.

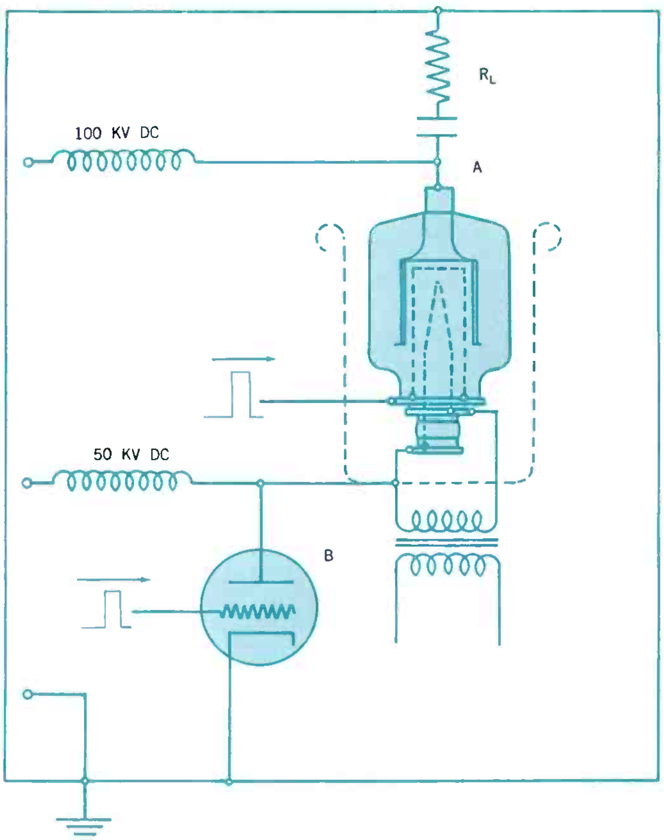

Figure 20 — Circuit for tubes in series. Dotted line shows position of electrostatic shield so that tube "A" never "sees" more than rated 50 kv.

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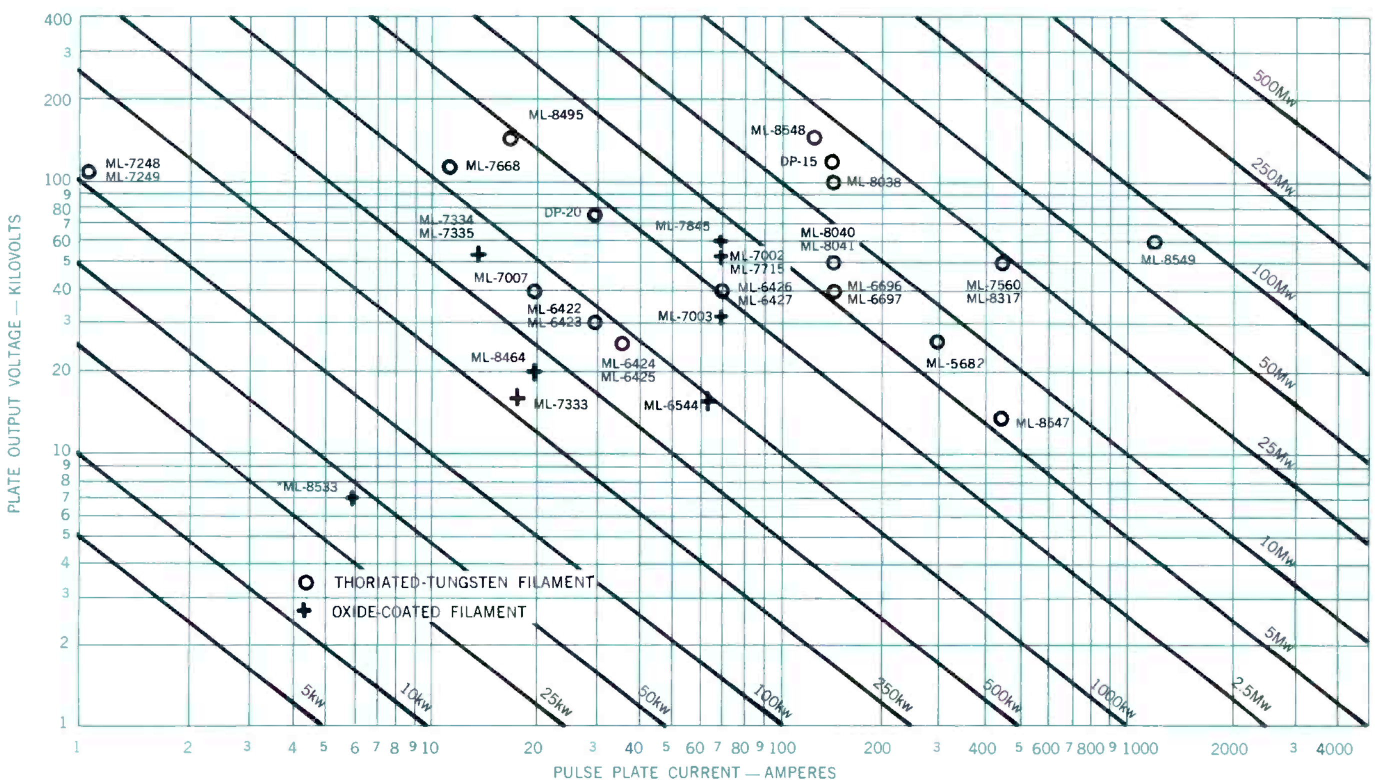
Appendix I

Switching Power of Machlett Pulse Tubes

Switching power of the current line of Machlett pulse tubes is indicated below. Each tube will deliver output current and voltage approximately up to values indicated by either an 0 or a +.

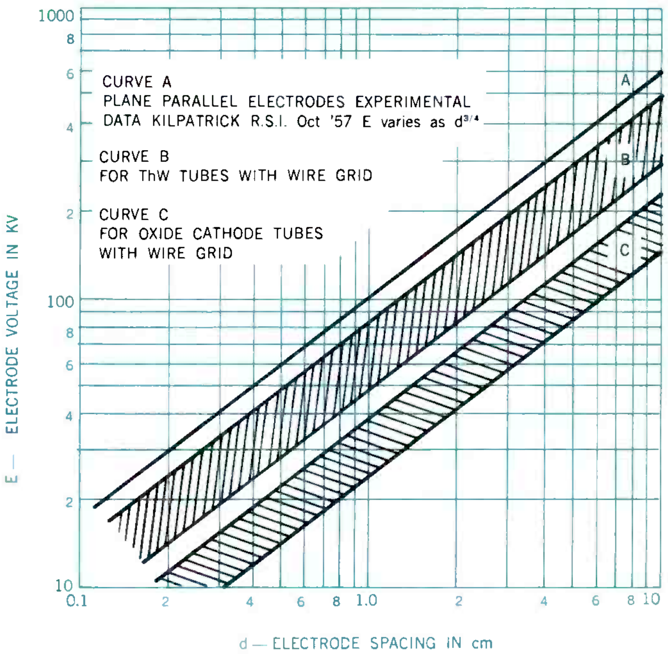
Lines of constant switching power through these coordinates show the range of current and voltage possible by the use of an output pulse transformer.



*UHF TRIODE. For data on other tubes of this type, Consult MACHLETT Engineering Department

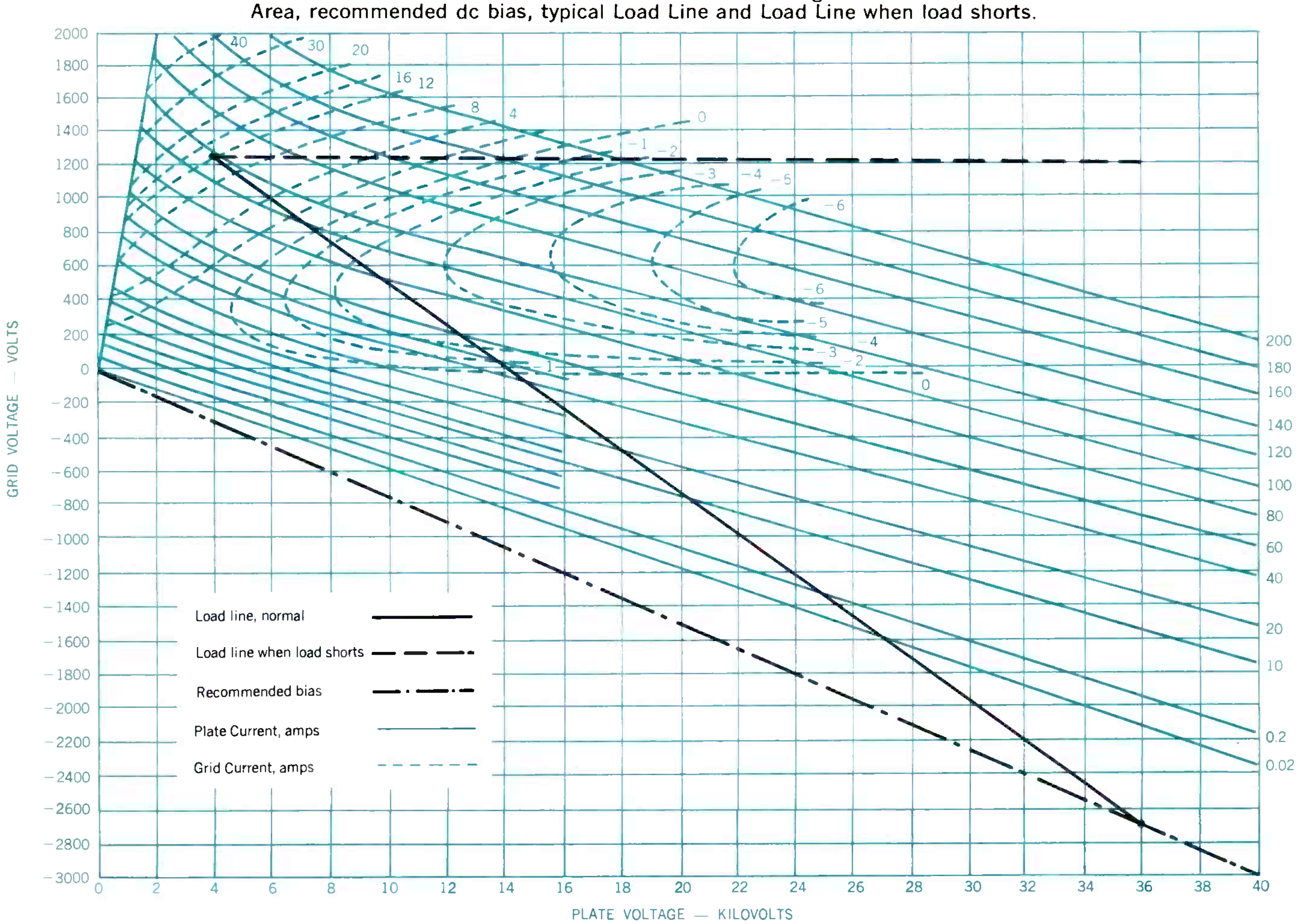
Appendix II

Anode Voltage Rating versus Outer Grid to Anode Spacing.



Appendix III

ML-6696 Constant Current Characteristic Curves showing Reverse Grid Current Area, recommended dc bias, typical Load Line and Load Line when load shorts.



New Machlett

ML-8549*
Super Power Triode

High Duty
Pulse Power
to 60 Mw

Description:

The ML-8549 is a super-power general-purpose water-cooled triode featuring extremely favorable plate-grid current division which results in minimum drive-power requirements. The cathode of this tube consists of sturdy self-supporting thoriated-tungsten filaments. The coaxial terminals have low inductance and high heat-dissipation capability. Insulating members are low-loss ceramic.

When used as a switch tube in hard-tube pulse modulators for radar or similar applications, it can deliver more than 60 Mw pulse output with pulse widths up to 10,000 microseconds at a duty factor of .06. When used as a pulsed rf amplifier operating at frequencies up to 30 Mc, the ML-8549 is capable of delivering 10 Mw, also at long pulse duration and high duty factors. When used as a pulsed modulator, a maximum plate voltage of 65 kVdc applies.

When operating as a Class C amplifier or oscillator at frequencies up to 30 Mc, the ML-8549 is capable of a continuous output in excess of 2.0 MW. The maximum CW plate voltage rating of 25 kVdc applies at frequencies up to 30 Mc.

The water-cooled anode of the ML-8549 is capable of dissipating up to 500 kW. The tube can be operated in air at maximum plate voltage ratings. The ML-8549 is supplied with an ion pump for maintaining a high vacuum during operation.

MAXIMUM RATINGS AND TYPICAL OPERATING CONDITIONS

Pulse Modulator or Pulse Amplifier

Maximum Ratings, Absolute Values

DC Plate Voltage	65	kV
Peak Plate Voltage	70	kv
DC Grid Voltage	−5000	V
Peak Negative Grid Voltage	−6000	v
Pulse Cathode Current	1200	a
Grid Dissipation	9	kW
Plate Dissipation	500	kW
Pulse Duration	10	ms
Duty Factor	.06	

Typical Operation

DC Plate Voltage	65	kV
DC Grid Voltage	−4000	V
Pulse Positive Grid Voltage	3000	v
Pulse Plate Current	1100	a
Pulse Grid Current	10	a
Pulse Driving Power	70	kw
Pulse Power Output	65	Mw
Pulse Plate Output Voltage	59	kv

Plate-Pulsed RF Power Amplifier and Oscillator Class C

Maximum Ratings, Absolute Values

Peak Plate Pulse Supply Voltage	40	kv
DC Grid Voltage	−4000	V
Pulse Cathode Current	1200	a
Grid Dissipation	9	kW
Plate Dissipation	500	kW
Pulse Duration	10	ms
Duty Factor	.06	

Typical Operation	Cathode Drive	Grid Drive	
Peak Plate Pulse Supply Voltage	38	38	kv
DC Grid Voltage	−2300	−2300	V
Peak RF Grid Voltage	5500	5500	v
Peak RF Plate Voltage	32	32	kv
Peak Plate Current from Pulse Supply	400	400	a
Peak RF Fundamental Plate Current	630	630	a
Peak Plate Dissipation	5.2	5.2	Mw
Plate Dissipation at .01 Duty	52	52	kW
Peak Driving Power	1750	33	kw
Peak Grid Dissipation	24	24	kw
RF Load Resistance	60	51	ohms
Peak Power Output	11.8‡	10	Mw

Developments

ML-8545 } ML-8546 } **

ML-8545 Vapor-Cooled Tetrode
ML-8546 Water-Cooled Tetrode
CW power to 330kW

Description:

The ML-8545 is a general-purpose vapor-cooled tetrode capable of 300 kW continuous output as a Class C amplifier or oscillator at frequencies up to 30 Mc.

The anode is designed to dissipate 150 kW during continuous operation and substantially higher power during momentary overloads or intermittent operation. Coaxial grid and cathode mounting structures provide low-inductance, high-dissipation rf terminals. The cathode consists of sturdy thoriated-tungsten filaments. Low-loss alumina ceramics are used for all insulation members.

Maximum ratings apply at frequencies up to 30 Mc. Useful power output can be obtained at higher frequencies with an appropriate reduction in ratings.

The ML-8546 is a water-cooled version of the ML-8545. The anode is designed to dissipate 125 kW.

MAXIMUM RATINGS AND TYPICAL OPERATING CONDITIONS
(Continuous Commercial Service)

RF Power Amplifier or Oscillator
Class C Telegraphy

(Key-down Condition per Tube Without Amplitude Modulation)

Maximum Ratings, Absolute Values

DC Plate Voltage	18000	Vdc
DC Screen-Grid (No. 2) Voltage	2500	Vdc
DC Control-Grid (No. 1) Voltage	-1200	Vdc
DC Plate Current	23	Adc
Screen-Grid Dissipation	3000	W
Control-Grid Dissipation	1000	W
Plate Input	420	kW
Plate Dissipation	150	kW

Typical Operation, Grid-Drive Circuit

DC Plate Voltage	16000	18000	Vdc
DC Screen-Grid Voltage	1500	1500	Vdc
DC Control-Grid Voltage	-850	-950	Vdc
Peak RF Grid Voltage	1060	1200	v
DC Plate Current	21	23	Adc
DC Screen-Grid Current	1.7	1.8	Adc
DC Control-Grid Current	.1	.3	Adc
Driving Power, approximate	100	350	W
Plate Output Power	250	330	kW
Plate Dissipation	85	90	kW

Plate-Modulated RF Power Amplifier
Class C Telephony

Carrier Condition Except Where Noted For Use With a Maximum Modulation Factor of 1.0

Maximum Ratings, Absolute Values

DC Plate Voltage	13000	Vdc
DC Screen-Grid Voltage	2000	Vdc
DC Control-Grid Voltage	-1200	Vdc
DC Plate Current	23	Adc
Screen-Grid Dissipation	3000	W
Control-Grid Dissipation	1000	W
Plate Dissipation	100	kW

Typical Operation, Grid-Drive Circuit

DC Plate Voltage	11000	13000	Vdc
DC Screen-Grid Voltage	750	750	Vdc
Peak AF Screen-Grid Voltage for 100% Modulation	750	750	v
DC Control-Grid Voltage	-500	-500	Vdc
Peak RF Grid Voltage	820	850	v
DC Plate Current	18	19	Adc
DC Screen-Grid Current	3.3	3.8	Adc
DC Control-Grid Current	2.3	2.8	Adc
Driving Power, approximate	1800	2200	W
Plate Output Power	135	180	kW
Plate Dissipation	60	70	kW

**Note: Data contained on page 42 are based on initial design and test criteria. Before using these data in final equipment designs, consult Machlett for possible revisions.*

***Proposed Technical Objective — Engineering Design Information.*

About the Authors

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Dr. Doolittle is Manager of Technology of The Machlett Laboratories, Inc., and has been responsible for the development of UHF and high power triodes and tetrodes as well as research on cathodes and allied subjects. He is also responsible for over-all scientific work of the engineering staff with particular emphasis on new products and processes. Dr. Doolittle is a fellow of the American Physical Society, and a Member of IEEE and the Electrochemical Society.

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Mr. C. F. Eggert received his BSEE degree from the State University of Iowa. Active in the technical communications field since 1955, Mr. Eggert has been an engineering writer, a publication engineer, and technical publications section supervisor. In his current position with Collins Radio Company, he is responsible for the preparation and publication of all technical information for the Collins airline communication and navigation product line. He prepared the maintenance and instruction manuals for the first Collins Distance Measuring Equipment (DME) used by commercial airlines.

Mr. Eggert is a member of the IEEE and is active in professional groups within the fields of aerospace and navigation electronics, engineering management, and engineering writing.

HENRY EGGERDING

Mr. Henry Eggerding is a Senior Project Engineer with ITT Federal Laboratories in Nutley, New Jersey. He has been a leading member of that company's pioneering team which introduced crystal control to the 1000 mc band in 1945. Since then he has contributed to the design of the numerous pulse transmitters for DME, TACAN, and IFF. More recently he has been active in the 4 gc altimeter field.

RICHARD W. DONOVAN

Mr. Richard W. Donovan received a B.S. in Electrical Engineering at the University of Kansas in 1957 and has performed graduate work in servomechanisms, transistor engineering, advanced mathematics and nuclear engineering. His special field includes pulse techniques, VHF transmitter and receiver design, microwave cavity design, microwave strip line design, UHF measurements and general electronic circuit design. He has responsibility for airborne DME and TACAN designs.

Most recent experience at Wilcox has been that of Project Group leader for the development of the Wilcox Model 814B General Aviation Transponder, Model 833 Distance Measuring Equipment, Model 914 Airline ATC Transponder and the Military 914X SIF System development sponsored by Wilcox, and the AN/PPN-16 X-Band Radar Beacon.

Professional affiliations include the Institute of Electrical and Electronic Engineers and the Armed Forces Communications and Electronics Association.

N. F. HAMILTON-PIERCY

Mr. N. F. Hamilton-Piercy, Development Engineer, Canadian Marconi Company, graduated from the Medway College of Technology in Light Electrical Engineering in 1960. His studies have included Advanced Transistor and Pulse Techniques, and he has had extensive training in environmental and electrical destructive and non-destructive testing and circuit design in radar and control systems. Mr. Hamilton-Piercy came to Canada in 1962 and is presently engaged in radio relay equipment design, chiefly in the rf power amplifier field.

[SPECIAL VIDICONS]

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1. Spectral response: near infrared; S-18; near ultraviolet or x-ray.

2. Fiber optics or standard faceplates.

3. Scanned area either ½″ x ⅜″ or 1″ x 1″.

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Machlett Special-Purpose Vidicons

ML-7351/ ML-7351A	1″	High sensitivity at low light levels
ML-2128G	1″	High contrast; fiber-optics input
ML-S522B	1″	Fast, near UV spectral response
ML-2128U	1″	Near UV; fiber-optics input
ML-2058G	2″	High resolution; 1.4″ diagonal image
ML-589	1″	X-ray sensitive; high contrast image
ML-2135G	2″	X-ray sensitive; 1.4″ diagonal image

For technical information write for our new brochure: Machlett Special-Purpose Vidicons. The Machlett Laboratories, Inc., Springdale, Conn. An affiliate of Raytheon Company.

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ELECTRON TUBE SPECIALIST

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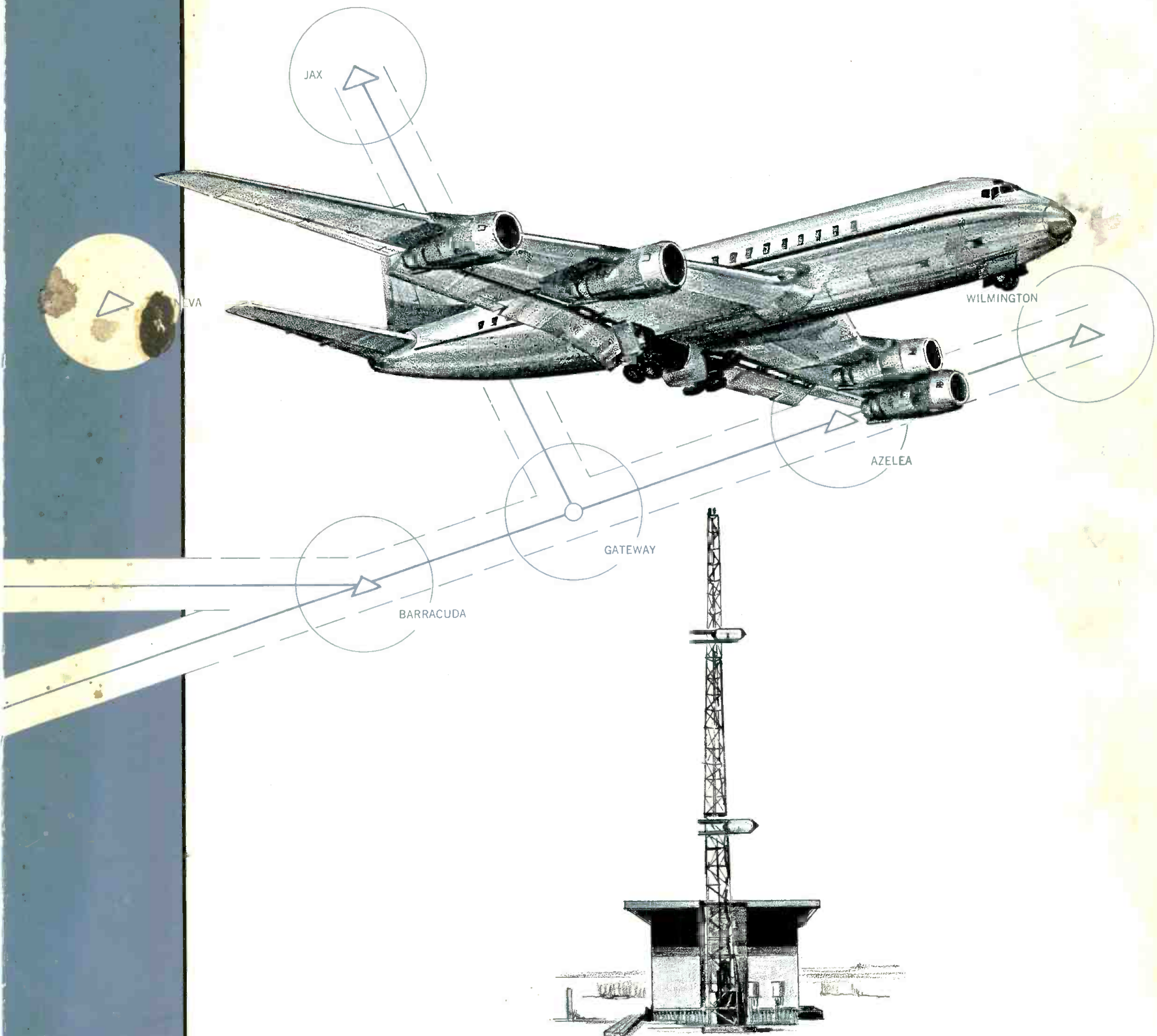

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IN THIS ISSUE

Cover:

Machlett planar triodes serve the nation's commercial airlines for air traffic control in DME and Transponder equipment.

Product Lines represented in this issue:

Small Power Tubes

Large Power Tubes

NOVEMBER 1964

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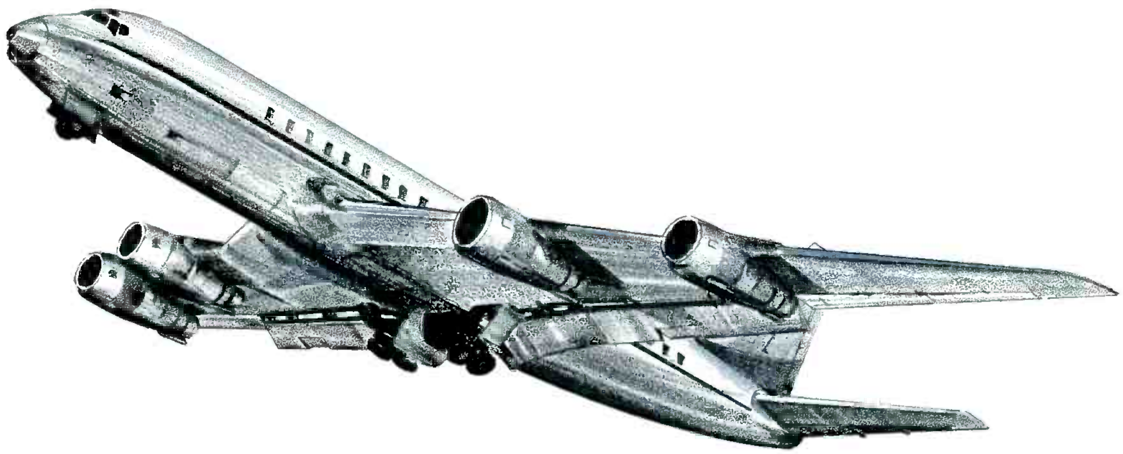
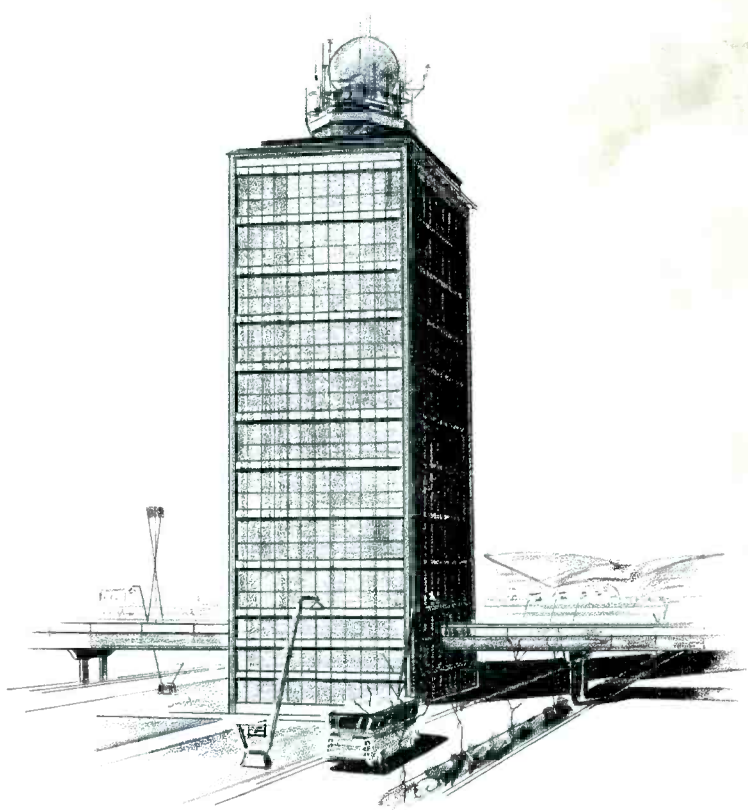
MACHLETT

ELECTRON TUBE SPECIALIST



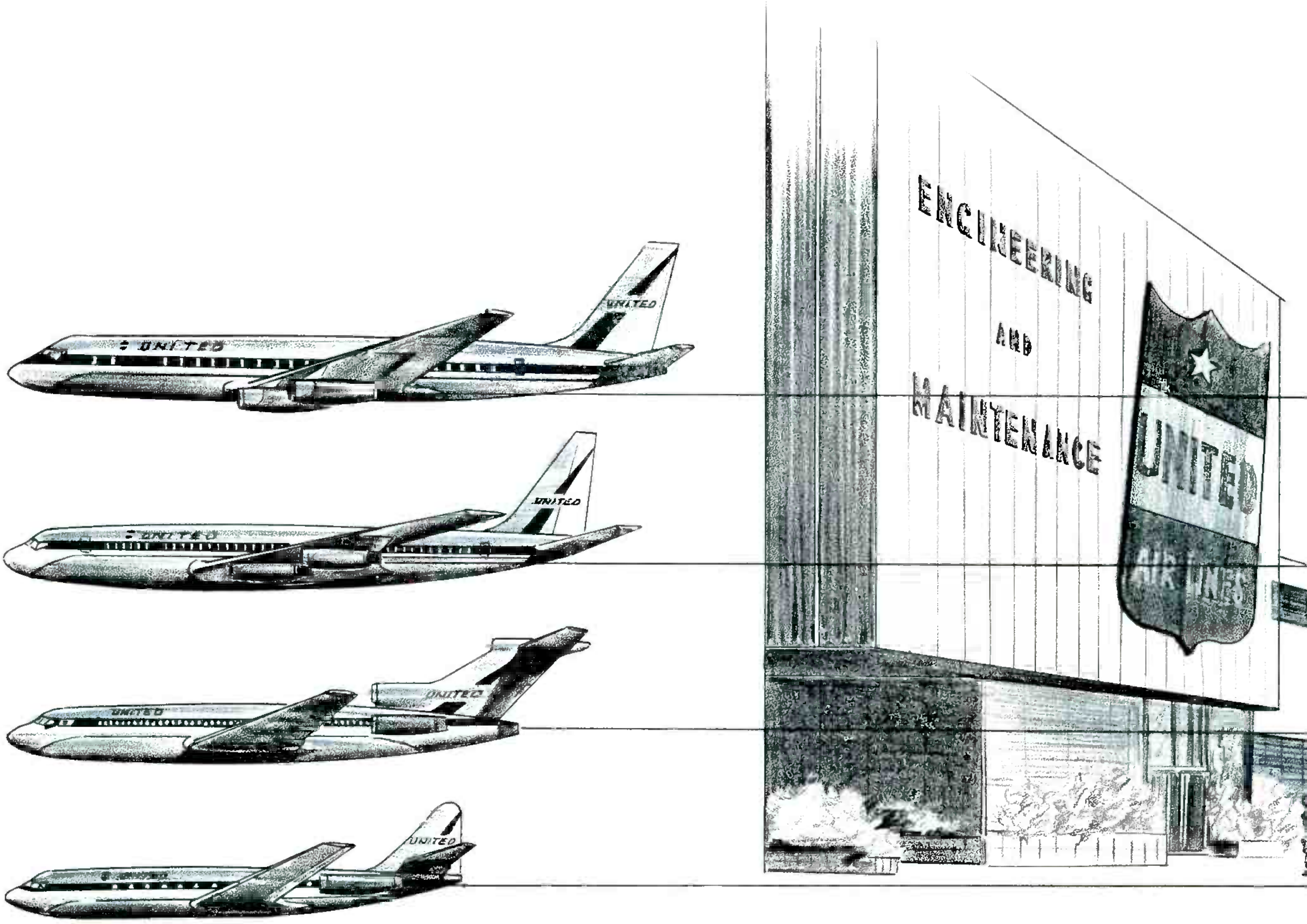
Introduction



It is quite possible that the term "maintenance" with its implications of repair, malfunction and after-hours drudgery should be re-coined so as to acknowledge the new scope of function included within the concept. "Maintenance", today, in the aviation industry is a unique, specialized and continuing production line — one generating its own statistics and response on a continuous input-output basis. It is a field calling for the best productive imagination to be found. The following pages of CATHODE PRESS indicate the discipline, the complexity and the range of this large, relatively unknown (to the public), but intensely active and important group.

All phases of electronic maintenance relating to the DME and Transponder — the general view, the base depot, the line or field shop, as well as indications of the future — are examined in this issue, Volume 21, Number 3. In addition, CATHODE PRESS takes a short and rather special flight to indicate one reason why the maintained equipment (which, incidentally, uses Machlett planar triodes) is around in the first place.

CATHODE PRESS, Volume 21, Number 2, was privileged to discuss the manufacturers' view of the DME and Transponder.



Historical Background
ATC Transponder

United Air Lines' contacts with the ATC Transponder system began prior to 1955 with participation in industry meetings to define the performance, size and interwiring characteristics of the forthcoming equipment. As equipment built to meet these requirements became available in 1957, United's Engineering personnel carried out a bench test program with several manufacturers' transponder units, in connection with plans to install transponder systems in piston aircraft. The transponder system at that time, was considerably simpler in concept than is presently the case, providing only one interrogation mode instead of 4, 64 reply codes instead of 4096, and with no requirements for sidelobe suppression or automatic selective reply features. During 1957, however, the system requirements were broadened to include four interrogation modes, two-pulse sidelobe suppression, and expansion capabilities from 64 to 4096 reply codes. Consequently, plans for fleet implementation were postponed pending development of equipment with these features. To acquire operational and maintenance experience, however, four RCA AVQ-60A and 4 Collins 621A-1 Transponders were purchased and operated in DC-7 aircraft through late 1957, 1958 and early 1959.

The operation and maintenance of these units prior to availability of special test equipment for the transponder system, required us to develop our own techniques and facilities for maintenance. The system knowledge acquired proved very valuable in subsequent operations.

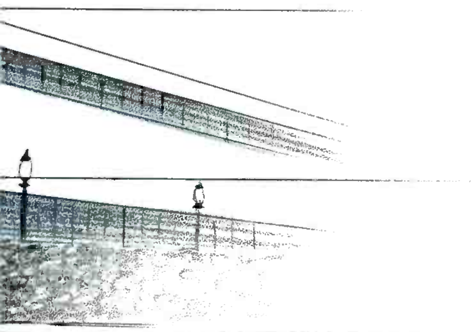
In 1959, United began fleet operation of Collins 621A-2 Transponders. A total of 95 of these units were procured for use in DC-8 and B-720 jets. In 1960 and 1961, United ordered 118 RCA AVQ-60B Transponders to cover needs for Caravelle aircraft and additional B-720 aircraft ordered, and for Viscount aircraft acquired through merger with Capital Airlines. Between procurement of the Collins and RCA Transponders, another system concept changed — 2-pulse sidelobe suppression requirements were replaced for United States operations with a new system using three interrogation pulses. RCA units were procured with the 3-pulse system, and modification of the Collins units was planned for a later time. In 1962 still another change in system requirements occurred; automatic selective reply requirements were added for Modes C and D to provide for automatic altitude reporting and for another unspecified automatic data link. In 1963, after reviewing our needs, orders were placed for 369 Collins 621A-3 units to provide for dual transponder systems in our B-727 and DC-8F aircraft; retrofit of a second system in DC-8, B-720 and Caravelle aircraft; for retirement of our 621A-2 units because of the system changes since their procurement; and, installa-

A General View of an Airline's Use of DME Transponder Equipment

Editor's Note:

United Air Lines operates the world's largest jet fleet and is the nation's largest domestic carrier. It now operates 139 jet aircraft, with 27 more Boeing 727s on order. United also operates 94 piston aircraft. This fleet serves 116 cities. In 1963 United carried 13,717,000 passengers and 133,459,000 ton-miles of freight.

CATHODE PRESS acknowledges with thanks the assistance given it by the Aircraft Engineering Department of United Airlines and, in particular, Mr. T. A. Ellison, Staff Engineer.



tion of a single transponder system in all piston aircraft (delayed since 1957 by the successive system changes). This order is now being received, and when complete, will make United Air Lines operator of more transponder equipment than any other civilian user. A modification program to add automatic altitude reporting to our AVQ-60 units is also in progress.

DME: Distance Measuring Equipment

As in the transponder system, United participated in industry activities to develop defining specifications prior to the existence of any civil DME equipment. During 1959 and 1960, DME system developments were closely monitored through bench and flight tests and demonstrations. All jet aircraft were ordered with complete aircraft wiring provisions for DME, and in 1960, modification projects to install DME wiring provisions in all piston aircraft began. In the Spring of 1961, it was decided that system developments justified activation of a single DME system in all jet aircraft, and orders were placed for Collins 860E-1 DME units for this purpose. These were delivered in the Fall of 1961, and the installation was completed in November 1961. Additional 860E-1 DME equipment was procured for a single system in Viscount aircraft early in 1962, for a total procurement of 235 860E-1 units. Further DME unit procurement was deferred, pending developments of solid state equipment. In 1963, orders were placed for 275 Collins 860E-2 units to be used for installation of single DME systems in all piston aircraft, for provision of dual systems in B-727 and DC-8F aircraft, and for addition of a dual system in all DC-8, B-720 and Caravelle aircraft. These installations are in progress at present, and will be complete in mid-1964, giving United Air Lines the largest DME equipped civil aircraft fleet in the world.

Maintenance Practices
Equipment Removal

Let's consider first the typical failure which begins the maintenance process. In the case of the ATC Transponder, the flight crew will probably be notified by radio from the ground Air Traffic Control Center that the transponder reply is missing or intermittent. In the case of the DME, the flight crew will probably observe that the flag on the DME indicator has dropped and the indicator is searching rather than displaying a mileage in an area where DME coverage should exist. Checks of the system and of the ground station will be made by the crew to verify that a failure has actually occurred. Although equipment failure is a daily business for the maintenance shop supporting a large fleet of DME or Transponder equipment, the failure is a rather infrequent occurrence for the individual flight crew member. Nine or ten months will have elapsed since the last Transponder

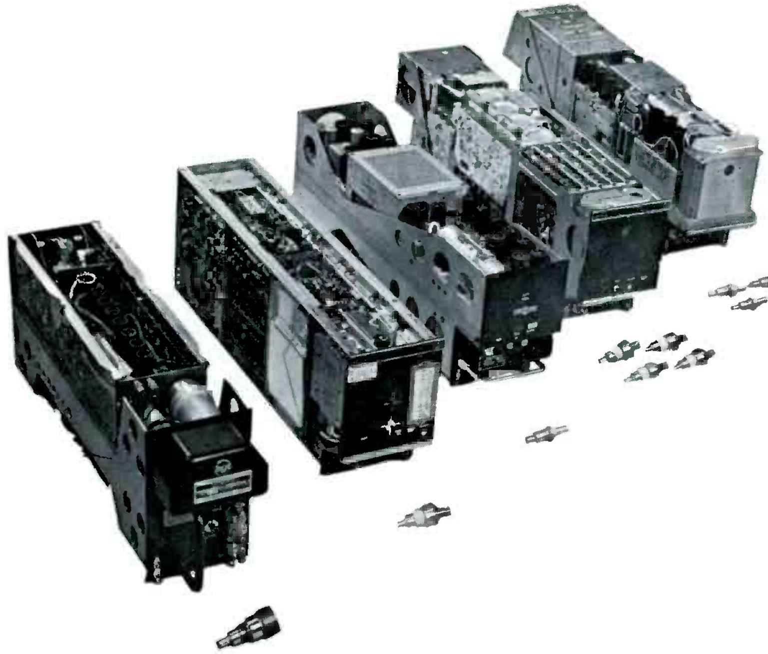
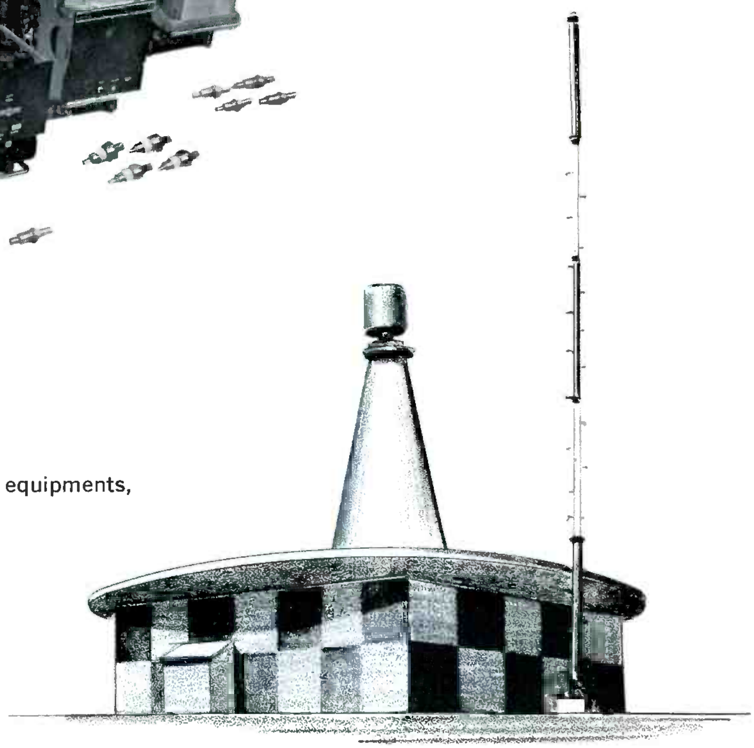


Figure 1 — United Airlines DME and Transponder equipments, shown with Machlett planar triodes used.



failure he experienced; five or six months since the last DME system failure on the average. Because of the protection of back-up systems or procedures, little or no alteration of the flight plan results. However, by radio, United's Line Maintenance coordinators and the FAA's Air Traffic Control Center are advised that the failure has occurred. In addition, a description of the failure is entered in the aircraft's flight log.

On arrival at the next Line Maintenance facility, a radio and electric system specialist will isolate the trouble and correct it, if appropriate, by replacing removable system components and routing them to the Overhaul Shop for repair. To assist him, he has available special ground test equipment and manuals covering the aircraft systems and their maintenance in detail.*

Radio Maintenance Shops

United operates five shops for the maintenance of radio and electronic equipment. The largest of these is located at our San Francisco Overhaul and Maintenance Base. Here a staff of 120 people in the Radio and Electronic Shops overhaul more than 400 different types of electronic assemblies or components, ranging from very simple devices to extremely complex radar or autopilot equipment. All types of electronic equipment operated by UAL can be overhauled at our San Francisco shops with the exception of equipment operated only in Viscount aircraft. The San Francisco Radio Shop occupies an area of approximately 10,000 square feet and has an investment of approximately $400,000 in specialized test equipment for check-out and operation of the components overhauled. Electrical and instrument components are not overhauled by the Radio Shop. These are handled in other shop areas, each roughly comparable in size to the Radio Shop.

Electroplating shops, sheet metal shops and machine shops are also available at United's San Francisco Base to support the radio shop (and others) in major repairs or modifications.

Viscount radio and electronic equipment is handled by a shop at United's Viscount Overhaul Base at the Washington National Airport. This shop employs approximately 35 people and deals in the same scope with Viscount equipment as does the San Francisco Shop with our other aircraft equipment.

United also maintains shops for maintenance of radio

*See page 18 for a detailed review of maintenance shop procedure.

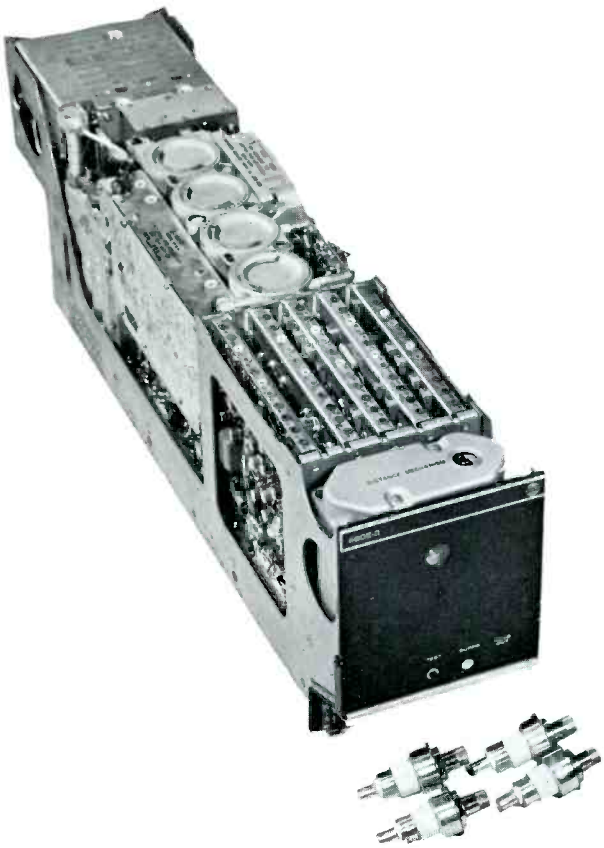


Figure 2 — Collins 860E—2 DME shown with ML-7815 planar triodes.

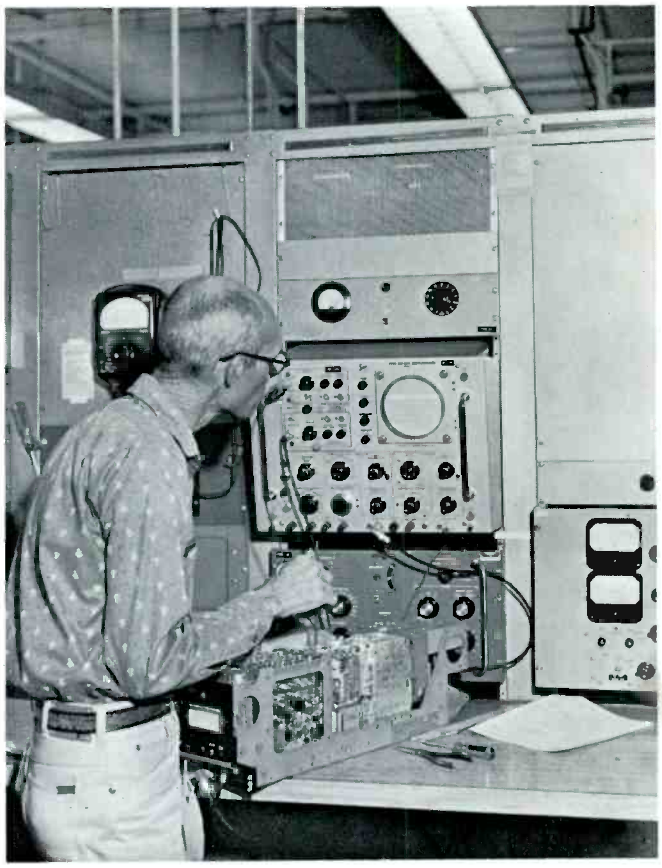


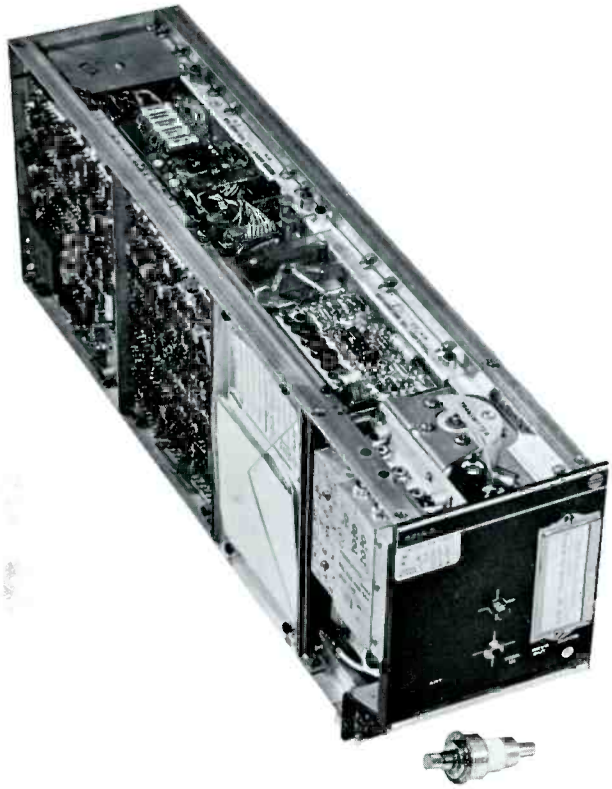
Figure 3 — DME Maintenance Test Position.

equipment at Seattle-Tacoma Airport, Chicago's O'Hare Airport, and Kennedy Field in New York. These shops have a combined employment of 30 to 40 people, and a combined output of radio equipment, of the types of equipment handled, comparable to that of the San Francisco Base. These shops handle only the heavily used types of radio equipment, however, and do no overhaul of autopilot equipment.

Transponder/DME Maintenance Practices

DME and ATC Transponder equipment specifically, is overhauled at our San Francisco, Chicago and New York shops. The same overhaul practices, test equipment and specifications are used at each location. The choice of shop is governed by the station at which the unit is removed from service. The incoming unit when received carries a tag with complete information on the circumstances surrounding the removal, including the pilot's description of the failure symptoms. The unit is turned over to an electronic mechanic specializing in maintenance of this type of equipment, and worked at a test station designed for and devoted exclusively to DME or to Transponder maintenance. The mechanic first attempts to verify, localize and correct the actual failure, using the data provided, and operating the unit with the signal environment and the balance of the aircraft system simulated by shop test equipment. This phase of the overhaul may vary considerably in difficulty and time required, but in general, with the test equipment, test data and check points in the unit circuitry, faults can be localized quite readily. For various reasons, the Line Mechanic may remove units from the aircraft on a precautionary basis if their performance is questioned. Consequently, a certain proportion of the "failed" units tested will be found to have no need of repair. In the DME and Transponder systems, this amounts to about 20% to 30% typically. All units carry a maintenance record covering one or more years of previous service to insure that actual faults, perhaps intermittent in nature, are not overlooked.

After fault location and correction, the modification record of the unit is checked to see if all known modifications or performance improvement changes have been accomplished. If not, such modifications are accomplished at this point. This type of modification for performance up-grading is a continual process throughout the years that the unit is used. At times, units may be called in specifically for such modifications. Modifications may originate from the equipment manufacturer, the airline shops, or engineering department,



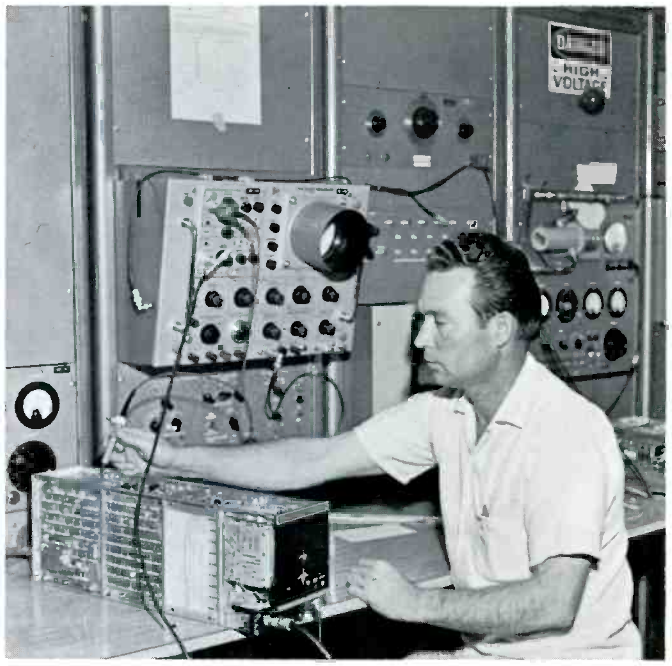


Figure 4 — (Left) Collins 621A-3 Transponder shown with ML-7815.

Figure 5 — (Right) Transponder Maintenance Test Position.

but are accomplished only if approved by United's Engineering Department, where control of the unit configuration and performance specifications resides.

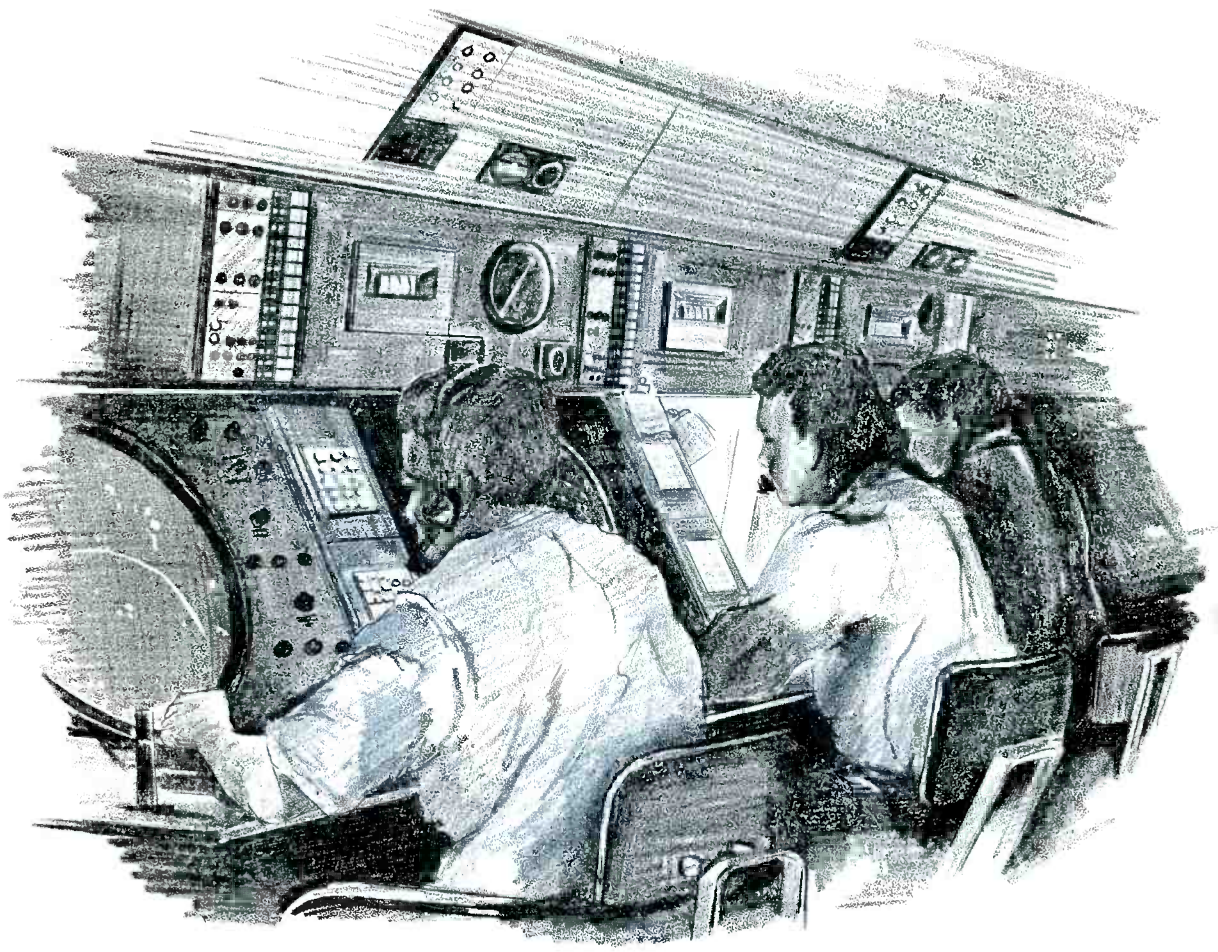
After completion of any necessary modifications, the unit is subjected to a comprehensive performance analysis. The tests conducted in this analysis and the specifications to be met are governed by specifications issued to the shops by United's Engineering Department. These tests and specifications are summarized for the mechanic in a highly condensed symbolic form on overhaul check sheets, which are filled-in with the test results for each unit overhauled. These tests in general insure that performance equal to or better than that of a "new" unit is obtained prior to release from overhaul. The check sheets are maintained in shop files as an overhaul record and may be consulted if questions arise about unit performance trends. The check sheet for the 860E-1 is a 6 page document calling out 44 separate performance specification areas, including such things as transmitter frequency, power and pulse shape, IF sensitivity and bandwidth, AGC action, decoder sensitivity and aperture, phantastron circuit operation, range gate tracking, distance accuracy, and so on. The ATC Transponder check sheet is a 3 page document and includes checks of receiver bandwidth, sensitivity and output, sidelobe suppression, decoder aperture, spike rejection and cross mode rejection, transmitter power, pulse shape, encoding, and other items for a total of 19 specification areas.

If the unit fails to meet any of specified requirements, the cause must be determined and corrected before release to service.

Units may be returned to the shop for reasons other than suspected failure. Units might be returned for example — for modification as mentioned, for analysis to collect performance data, or in some cases, because of expiration of a fixed calendar time or flight time. Regardless of the reason for removal or the time since last overhaul, the complete overhaul procedure and specifications apply.

Airline Electronic Engineering

In the previous sections, some of the functions of the airline engineer have been mentioned. The typical airline engineer of today holds a degree in Engineering or related sciences. Usually, in addition, he has had some previous experience or interest in the aviation industry. In addition to his electronic technical background, he must have acquired



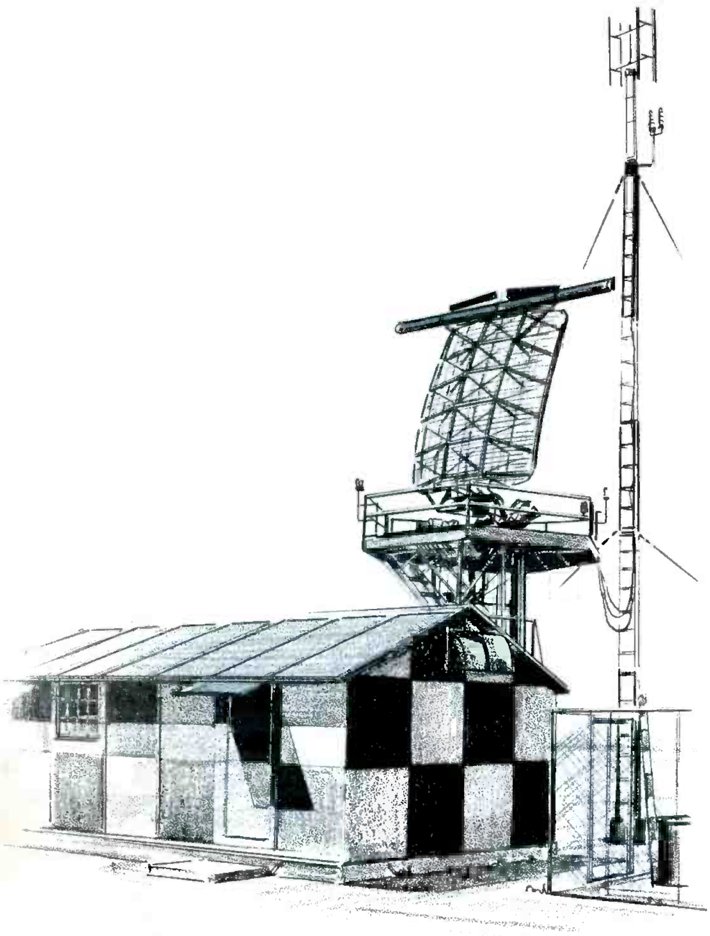
a thorough knowledge of the problems of operation of the aircraft in scheduled service and a good background in the practices and the references of the various aircraft manufacturers with respect to system, and to some extent, airframe design.

United Air Lines, as might be expected to support operation of the largest civil jet fleet, has one of the largest, if not the largest, Engineering staff in the airline industry. The function of the airline engineer includes a wide variety of responsibilities, falling somewhere between those of a field engineer and electronic system design engineer. He has much the same field performance monitoring responsibilities as the former, but more direct responsibility to correct the problems uncovered. He has responsibility for determining the extent and the specifications for equipment overhaul to insure that operation and reliability of the system is satisfactory and that legal requirements are met. If reliability or operational problems are encountered he may work with the equipment or component manufacturer to investigate the problems and determine the corrective action necessary, or he may investigate and develop corrections himself; depending upon circumstances. Corrective actions may include design of equipment modifications or changes to overhaul or operational practices.

Through the Airlines Electronic Engineering Committee of Aeronautical Radio, Incorporated, airlines coordinate development of descriptive "Characteristics" for new equipment. These provide design guidance to manufacturers by defining the system functions and performance, equipment, size, and interwiring.

The airline engineer, in cooperation with manufacturer's design engineers, may work in AEEC subcommittee activities to prepare new system "Characteristics" and revise and up-date old ones. The result is to broaden the market for the manufacturer by consolidating and defining airline equipment needs. The airline benefits from this equipment standardization by achieving interchangeability between manufacturer's equipments and from aircraft to aircraft, by reduction of equipment costs in comparison to "custom tailored" designs, and, of great importance in new aircraft procurement, through the ability to specify aircraft system wiring and mounting provisions in advance of actual procurement of the system hardware.

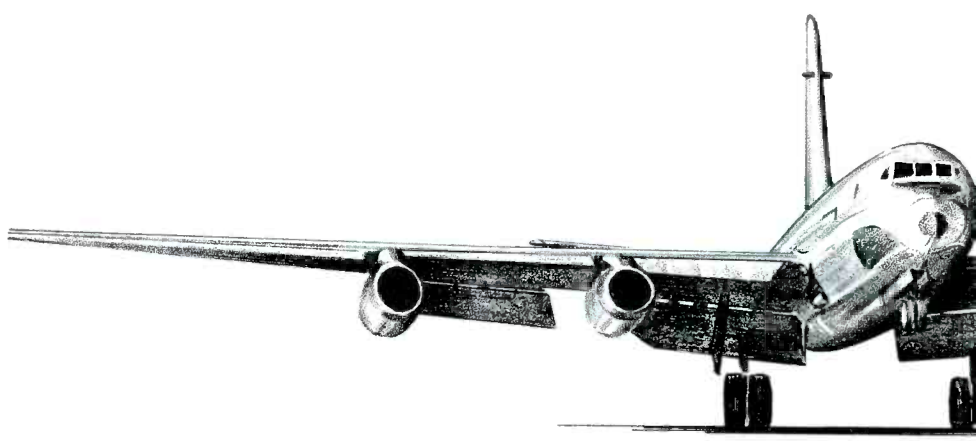
During periods of new aircraft or equipment procurement, United's Engineering Department assists in review and selection of the equipment best suited to United Air Lines needs,



in cooperation with Flight Operations or Ground Services Departments affected. These reviews often involve prolonged and sophisticated function test programs conducted by the Engineering Department. Prior to selection of new aircraft, a detailed specification of the configuration and performance of the aircraft and its systems is prepared by the Engineering Department for each aircraft under consideration. Forecasts of operating capabilities and costs of the aircraft on United's routes are also prepared to assist in the selection.

In the airline radio and electronic industry, there exists an unusually high degree of cooperative effort between the airline user, the equipment manufacturer, and the electronic component manufacturer. At its best, this relationship permits each to operate as a specialist in his own area, cooperating to achieve mutual goals of improved system, unit and component reliability. The airline staff works primarily to locate and diagnose problem areas and to provide data to the equipment and component manufacturers. They, in turn, assist in the problem diagnosis, and develop suitable corrective action or product modifications. These are incorporated into the equipment by the airline and the effectiveness of the correction evaluated by the airline staff.

As an example of the effectiveness of this type of cooperation, the attached figure shows the performance improvement obtained over a two year period of operation of a unit using UHF planar triodes in the transmitter section. Quite frequently, new equipment being introduced into service will



experience a "shake down" period of higher than normal removal rate. Operation in real time and the real environment often exposes problems not predicted during the equipment development. Among the problems in this particular case was a condition causing short life of the transmitter tubes. As this problem became apparent, both the equipment manufacturer and tube manufacturers responded with corrective action. Incorporation of these corrections and improved tubes began in February and was essentially complete in April of the first year with very gratifying results. As can be seen, the equipment irregular removal rate showed a rapid short term improvement and continuing long term decrease. Corresponding benefits in transmitter tube mean-time between failures are shown by the horizontally marked bar graphs. Since there tends to be a gratuitous increase in component life by any reduction of unit irregular removal rate, through decreased frequency of overhaul, the diagonally marked bar graphs are shown as confirmation of the improvement in tube life. They indicate a reduction in the ratio of tube removals and removal opportunities.

Examples of this type of manufacturer-airline cooperative product follow-up program could be found in many other cases. While product follow-up relationships exist in many industries, those of the airline industry are particularly successful. This is due in large part to the effort made in the airline industry to obtain meaningful performance information for the manufacturer and to the cooperative response obtained from the manufacturers.

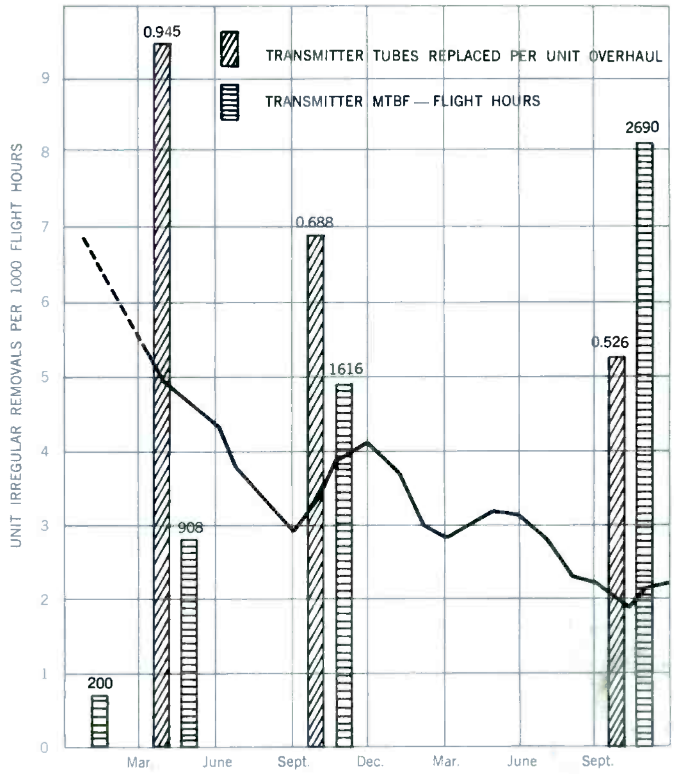
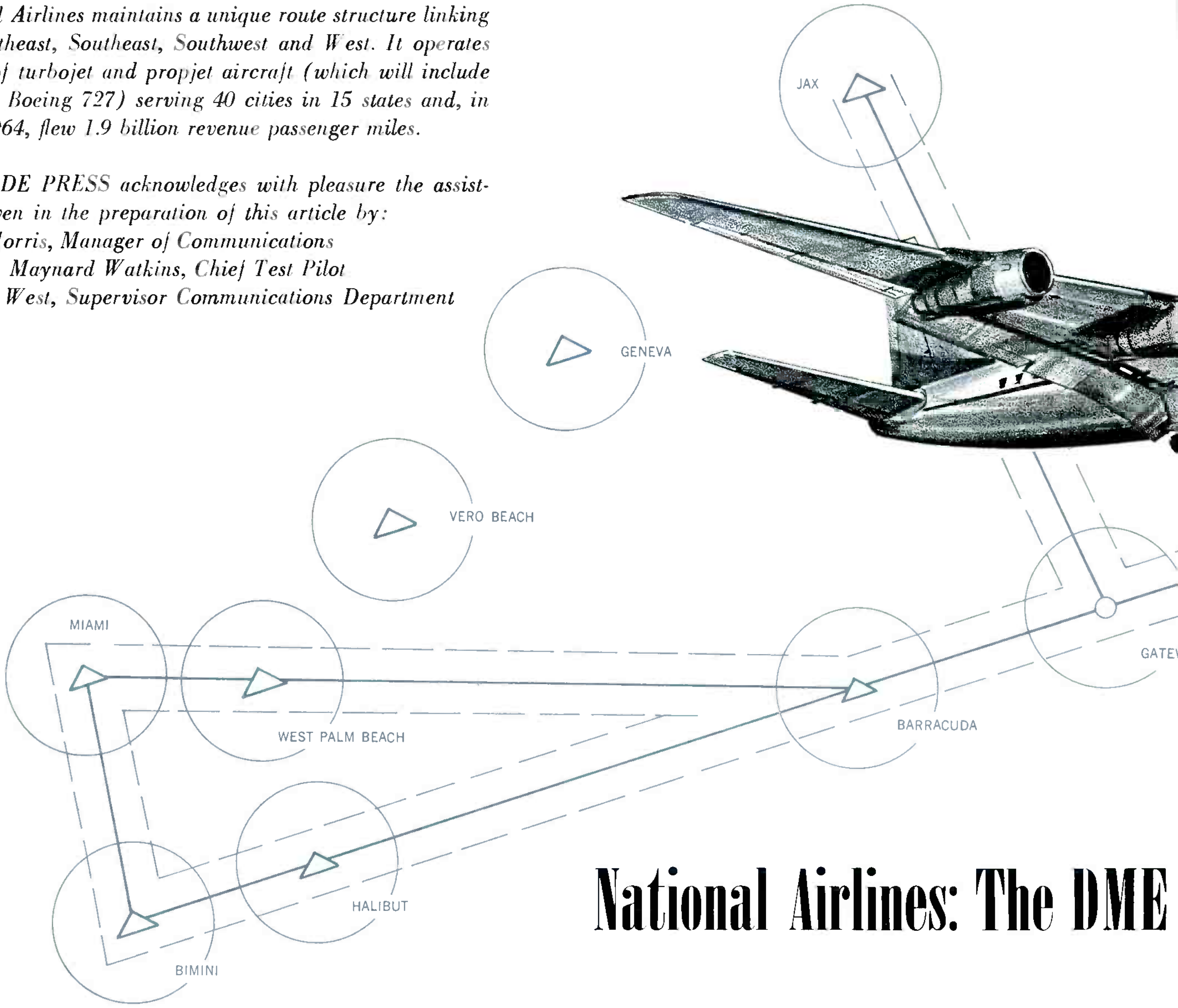


Figure 6 — Improved Tube Life—Longer Transmitter MTBF periods.

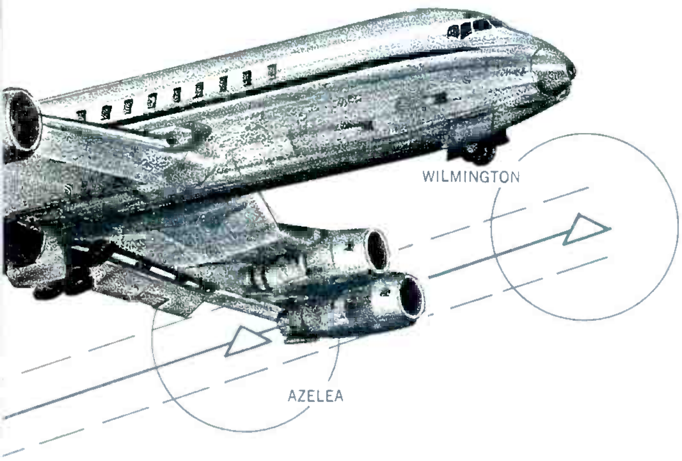
Editor's Note:
National Airlines maintains a unique route structure linking the Northeast, Southeast, Southwest and West. It operates a fleet of turbojet and propjet aircraft (which will include the new Boeing 727) serving 40 cities in 15 states and, in fiscal 1964, flew 1.9 billion revenue passenger miles.

CATHODE PRESS acknowledges with pleasure the assistance given in the preparation of this article by:
W. E. Morris, Manager of Communications
Capt. G. Maynard Watkins, Chief Test Pilot
Merwin West, Supervisor Communications Department



National Airlines: The DME

Although not a few of us can remember when low level flight might have meant tree leaves (or worse) in the air intake, "low level" for sometime now has referred to any flight altitude below 14,000 feet. It is in this busy lower pool of air (of all flights today 93% are made below 18,000′) that the shorter distance flights, 50 to 500 miles, are made. Here a captain and co-pilot flying direct from one city to another may even be concerned with his en route navigation for a shorter period of time than his terminal approach and landing procedures. A somewhat more normal low level flight situation might require flight plan calling for 3, 4 or more airway changes prior to nearing the destination terminal. During the relatively brief, and certainly concentrated time the pilots have much to do beside navigate. While one man devotes full attention to the control and flight of the aircraft the other "works" the



and Transponder in Action

VHF communications radio (the Captain monitors the radio through his headset) making position reports to the Air Traffic Control, writing down instructions received by them; providing company dispatchers with position reports, weather data, fuel supply and so on. Therefore any device which frees a pilot to concentrate on his many other duties, as well as one which provides him with great accuracy — and the confident feeling which accompanies this — is to be highly desired. Such, of course, is the DME, a device which is to the pilot as the Transponder is to the traffic controller. Each instrument in its sphere immensely relieves the operating individual of the burden of detail and provides him with exact and instantaneous units of information.

A DME in Action

NAL Flight 383, its flight plan (IFR) filed to Norfolk,

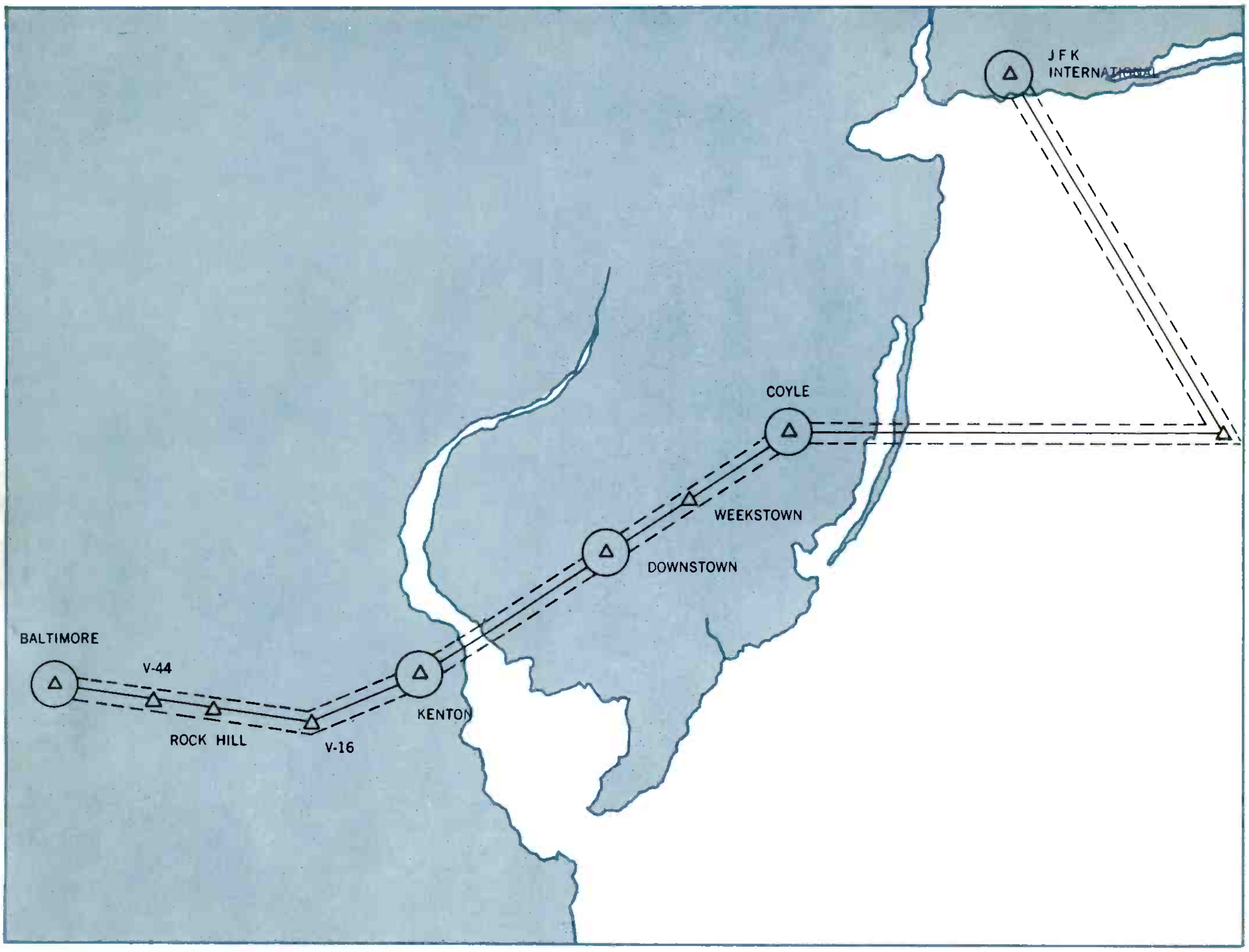


Figure 1 — DME equipment in use on the New York-Baltimore leg of a New York-Norfolk "low-level" flight. "Low level" includes all flights to 14,000 feet.

is now airborne after clearance for takeoff on Runway "31". Departure Control picks up the plane and identifies it as it begins the initial climb out of JFK. The transponder is set to Mode A, Code 10 indicating a climbing attitude. A heading of 290° (established as soon as possible to minimize noise) is maintained to 1000 feet followed by a left turn (in this case) to 160° holding this heading until cleared to turn on course. Still climbing, NAL "383" crosses the JFK VORTAC 224 radial at an altitude of about 2500 feet. Cleared for a turn on course, the transponder, still on Mode A, is set to Code 1 (0 to 14,500 feet). Figure 1, above.

Shortly following this the pilot is asked for his ETA to Coyle, a VORTAC station approximately halfway between Lakehurst and Atlantic City, N. J. Within one-half minute or less the answer is relayed over the VHF communications radio to JFK. For close-in ETA's a quick figure of TAS (True Airspeed) divided by 60 (to get miles per minute) times DME miles to go to Coyle provides a rapid and useful figure. (For longer distances and times ground speed is, of course, used.) Protractor, compass, even radio fixes, have been eliminated; a useful rate of speed has been found in a tenth or a twentieth of conventional navigation time. But this has been a clear day. Had the flight been over the clouds the only ETA for Coyle would be given when the plane was over Coyle. Now both the National dispatcher and the FAA controller know at once — and under any condition. Once at Coyle, Victor Airway 16 is picked up and Flight 383 is off and away on a heading of 246° with a total distance (as given by the chart) of 62 miles to the next VORTAC/DME station (which is the second VOR station along the route and almost exactly on course).

Along a Victor (or VOR airway) are plotted a number of compulsory/option checkpoints. Pre-DME in concept these points represent intersection of the VOR radials and provide a reasonably rapid means of establishing air-to-ground position reports. Such an intersection is located at

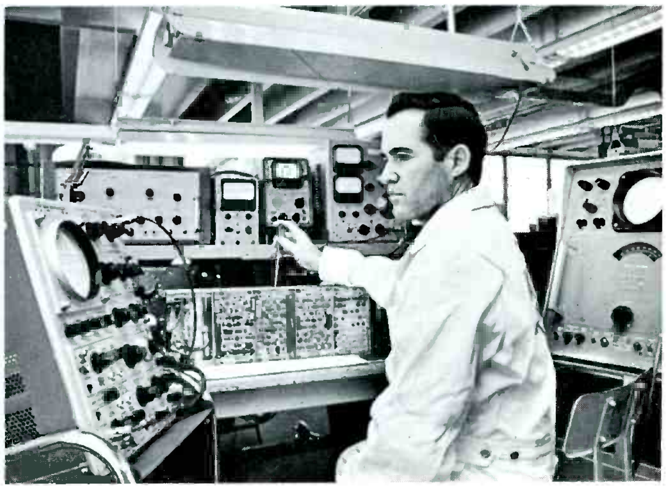
Weekstown, 13 miles southwest of Coyle and is the crossing of the Yardley (116.2 mc; ARD) 171° radial and the Coyle (113.4 mc; CYN) 246° radial. If necessary this point could be used to cross-check DME miles or, of course, as a back-up or substitute. Much more direct, however, is to follow along on the Coyle radial and pay out the line, so to speak, with the DME indicator showing the miles from Coyle. Now the pilot has an infinite — or nearly so — number of checkpoints and can report his position with reference to one reading only; for his own information he may maintain a continual running reference.

At Millville he reports position as required and concentrates next on Kenton 32 miles distant along the Victor-16 airway. At Kenton he prepares for a course change from Victor 16 to Victor Airway 44, to bring him into Friendship International. Since there will be no DME signal at the airway junction to Victor 44, NAL 383 tunes to Kenton and waits for an 18 mile DME indication (showing position away from the station); he uses this reading, together with this VOR radial, to establish position for the turn. But he can quickly get a fix at this junction by reading ahead to Friendship and establishing (with a half minute or less) that his DME reading to Friendship is 38 miles. Prior to DME he would have had to plot two or more radio bearings, determine his position by the interception of the beams and turn accordingly. Useful — but much slower, much less accurate.

Assume though that he is advised of turbulence on or near Victor 44 as he approaches the turn off from Victor 16. He is requested to hold at Rock Hall, for example. Because of his continuous distance reference he locates Rock Hall at once and proceeds to hold as directed. Permitted to proceed he nears Friendship, Code 14 is placed on the Transponder; Code 4 is set in after landing. The first of the four stops of the Norfolk run has been completed — accurately, and on time.

Figure 2 — The aircraft radio truck delivers a DME to a waiting DC-8. Dual DME and Transponder installations are used on these and other National aircraft.

Figure 3 — A Federal ITT DME is checked out in the Radio Shop. Machlett ML-7815 tubes are used in this equipment.



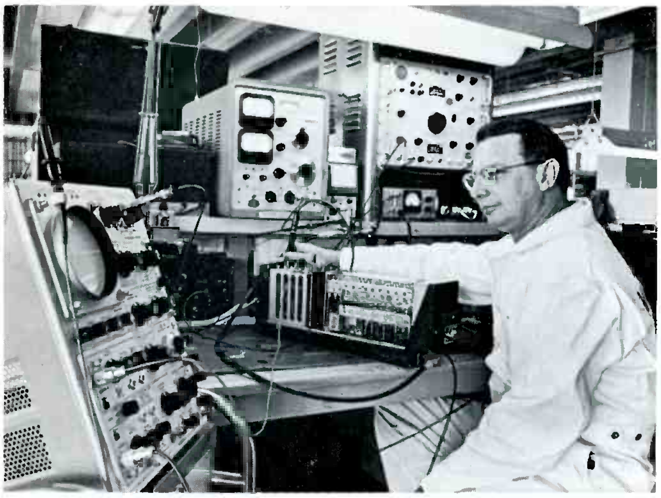


Figure 4 — The Collins 621-A transponder is adjusted in for peak performance. Cavity for the Machlett ML-7815 is visible at the left of the transponder unit.

"Hi-Level"

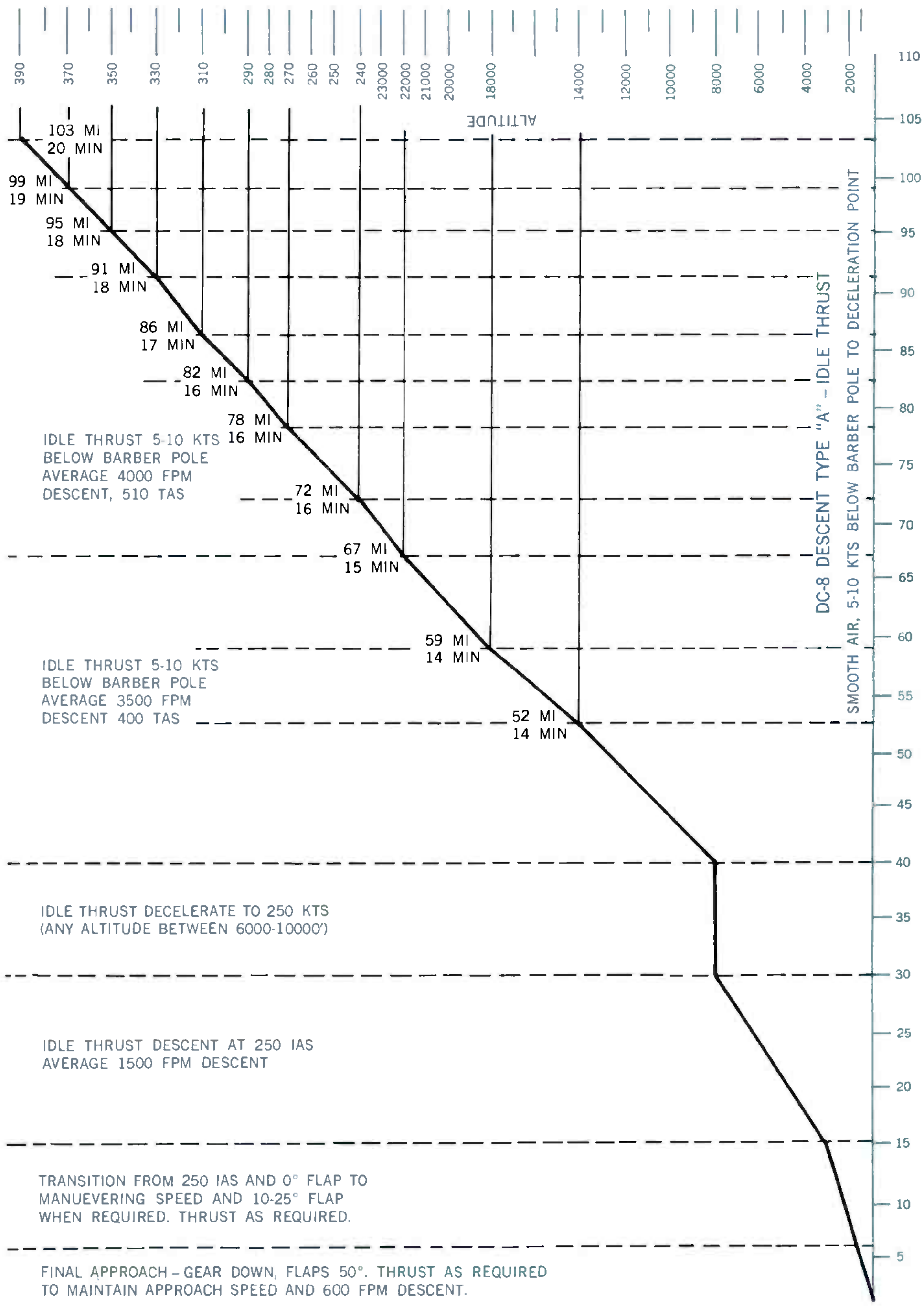
With a muted nod to Biscayne Boulevard and Collins Avenue, NAL Jet Flight 80 proceeds outward bound from Miami to New York. Gaining altitude imperceptibly but rapidly as it reaches its on-course heading (008°) it rushes northward up the airways slot at 31,000′ past Cape Kennedy toward its first landfall at Carolina Beach. A DME reading off Jacksonville confirms the plane's position as 157 miles due east (as indicated on the chart). This is important because north south slot (from Bimini Island, south, to Wilmington, South Carolina, north) is only five miles wide. It is also about one-half minute wide at the ground speed of NAL 80. Radio bearings from Daytona, Jacksonville or Savannah could be used to maintain airspace position in this channel but these are slow (and, at this distance reception may not always be good); waiting for needle deflection to average out takes a considerable time at 600 mph.

Figure 5 — John F. Kennedy International Airport.
Courtesy of The Port of New York Authority

The DME, like an unusual flashlight which, instead of illuminating a target, obligingly tells you how far away it is, supersedes the Radio compass in both speed and accuracy. (As a matter of fact, National's DME's and those of the other airlines have been used not only to confirm but to correct mileages listed on the navigation charts). Using DME mileage references, similar to those described for the low-level flight, NAL 80 proceeds on course toward its destination.

Code 21 (above 24,000 feet) had been set in on flight 80's transponder, but this changes now to Code 14 as it begins its descent into JFK. Suppose now that incoming traffic at the terminal area has built up somewhat and the plane is requested to hold. In pre-DME days he would have "held" in relation to the intersection of radio range courses or the intersection of VOR radials. In each instance the holding pattern would have been determined by a time run (inbound or outbound) on a leg, a standard turn and an-

Figure 6 — Accurate mileage determination made possible by DME allows use of fuel saving schedules such as shown below.



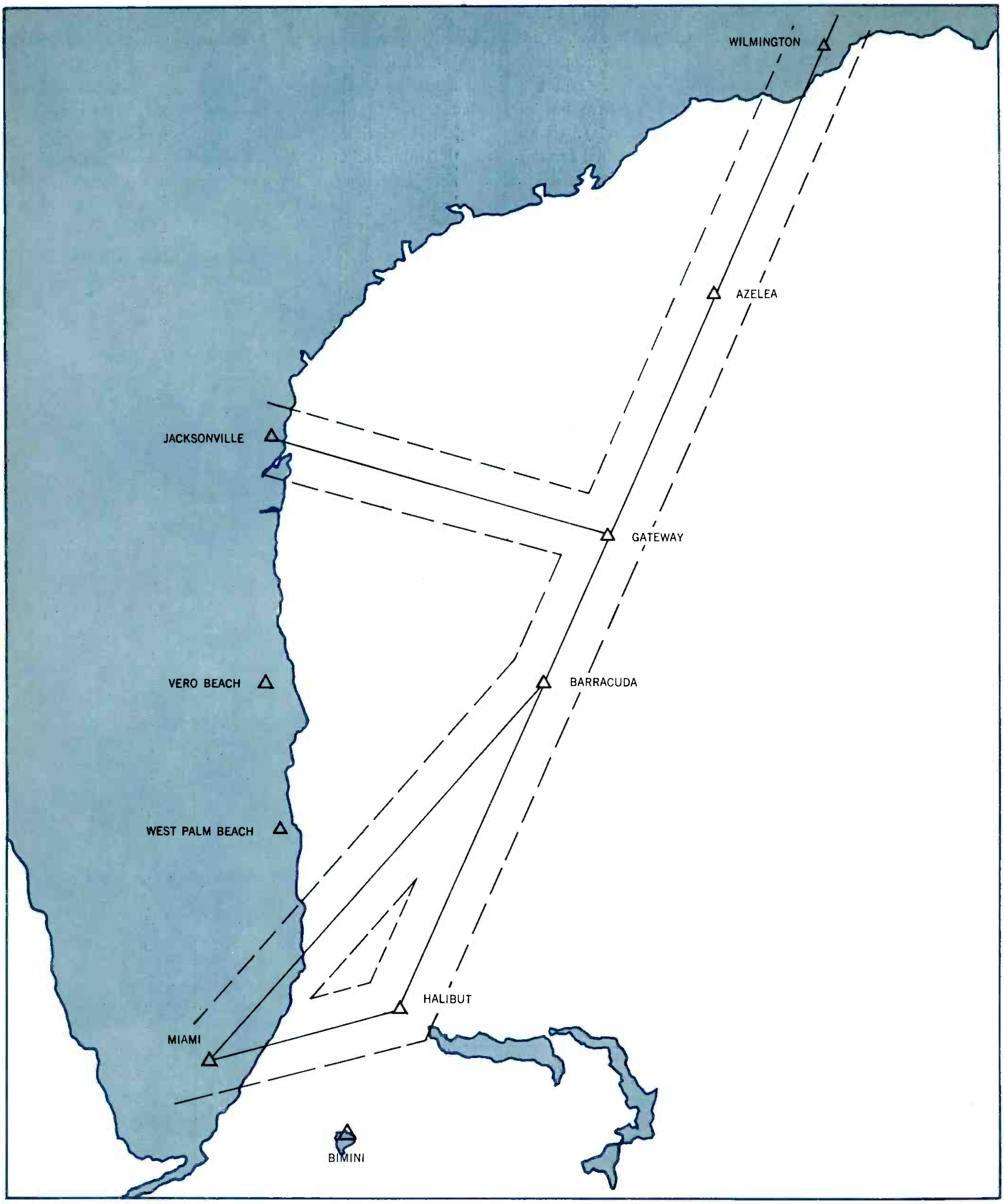
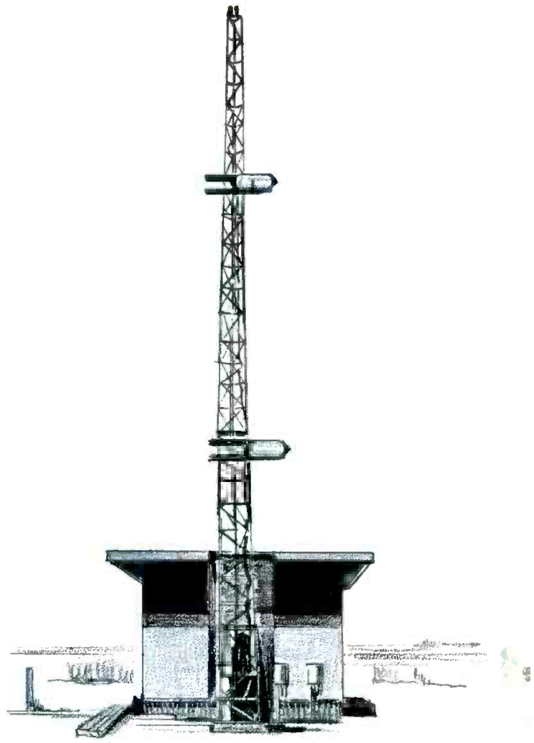


Figure 7 — DME equipment in use on the Miami-Wilmington (S.C.) leg of a Miami-New York "high-level" flight. "High-level" includes all flights above 24,000 feet.

other timed run. Timing would have to account for wind velocity — no simple matter when winds aloft may be upwards of 100 knots. Reading a second hand and compensating for wind drift and for ground speed variation take pilot time and additional concentration. Using the DME odometer for holding pattern information has a clear advantage. Once again, the pre-DME reference point for establishing the holding pattern had been the intersection of VOR radials — (and it had been necessary to re-establish this point after each circuit of the pattern). Now, the instructions, "Hold at a point 15 miles from the navaid in a standard pattern," require minimum navigational attention for accurate compliance.

Cleared to leave the holding pattern NAL 80 now cleared to go direct to the airport on a DME radius keeping a constant rate of turn and constant mileage indication on the odometer. Constant reference equals constant control — and, once again, on time arrival.



Many of the uses of DME have not been referred to in these brief sketches of the low and high level flights. One additional mention, though, is of interest. Since it costs about $20.00 a minute to keep a large jet flying it is apparent that any thing which saves time will, in short order, save a significant sum of money. In this connection descent from altitude gains significance. A turbojet flying with a favorable wind at high altitude wishes to maintain that altitude as long as possible and to descend, consistent with safety, as fast as possible so as to remain in the denser air for the shortest time. In the western terminal areas — nearing the completion, for example of a Miami-Los Angeles flight — a straight in descent, made at rates determined by the pilot, is frequently authorized. Since the pilot knows his distance from the destination airport to within a tenth of a mile, he can initiate his minute-saving, money saving descent with the knowledge that he will complete his descent at just the right place. The accompanying table, Figure 6, for "idle thrust" indicates his options. At 39,000′, for instance, he could begin Descent Type "A" with idle thrust (engines idling) 103 miles and 20 minutes from the airport. (For the meaning of "below the barber pole" see p. 31, KIFIS reference). On the basis of only 20 flights a day and saving a total of only 20 minutes a carrier would realize a total saving of approximately $12,000 over a month's period. DME, then, not only pays in safety, but pays for itself in profit.

Editor's Note:

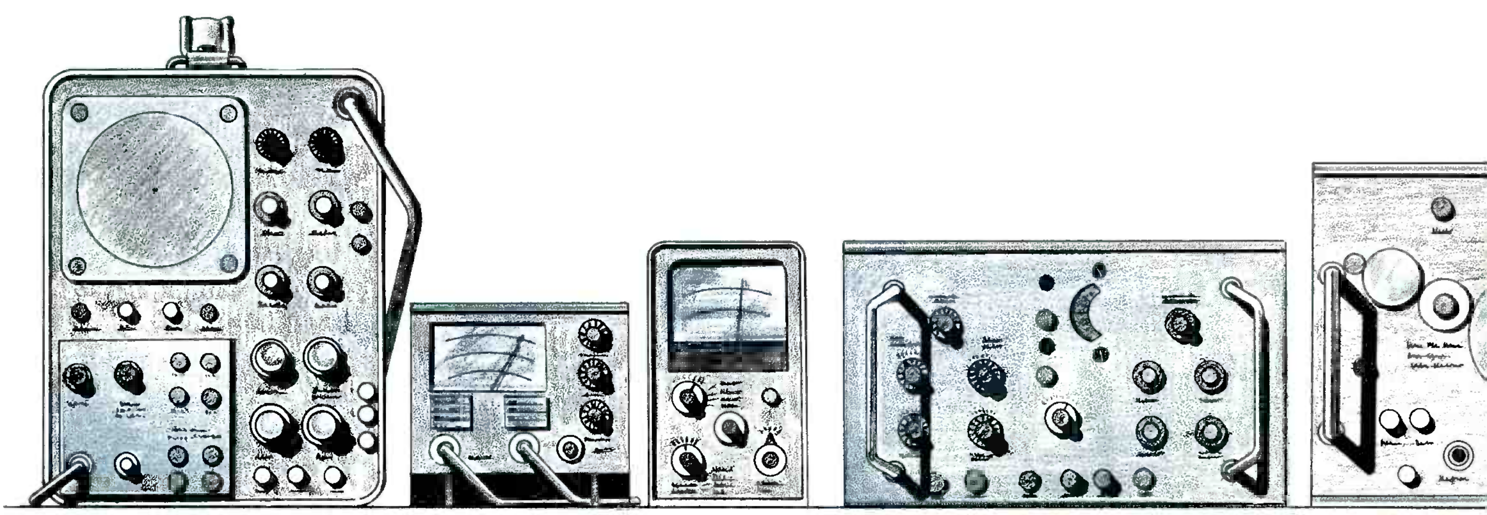
Pan American Airways is the world's largest carrier of international air passengers and air cargo. It operates a fleet of 67 jet aircraft to over 100 cities in 86 lands around the globe. Pan American, in 1963, carried 4,833,000 passengers and 200,000,000 ton-miles of air freight. Pan American has ordered 15 U.S.-built supersonic transport aircraft and six Anglo-French "Concorde" supersonic aircraft.

Pan American — Overseas Division —

One of the Divisions of Pan American World Airways, the Overseas Division, is headquartered at the John F. Kennedy International Airport. Comprised of over *15,000* employees, this Division schedules and operates as many as 80 departures daily. The blue and white Jet Clippers leaving for points from London to Calcutta maintain an especially busy traffic on the high density North Atlantic routes. Of the several groups included in the Overseas Division (Operations, Maintenance, and Flight) one of the busiest is the two-shift a day electronic maintenance overhaul group. Not only are they responsible for the electronic gear on a large number of aircraft, but typical of the standards that they and similar groups throughout the industry maintain, each individual equipment overhaul involves a minutely detailed examination taking on an average of 4 to 7 hours. Add together all the electronic units maintained and the answer becomes, in this case, a two-shift operation.

Whereas high density units (electronics, jet engines) are maintained at JFK, air frames are serviced at Miami where the "barn" doors can stay open all the year. Although JFK has prime responsibility for all "jet electronics", there is a Radio Engineering group at Miami which handles electronics for piston aircraft. A large radio shop, similar to the one at JFK, handles repairs for all types of aircraft, including jets flying the South American routes. And at San Francisco, electronics for the Pacific air fleet is kept in trim; while the planes flying the middle and far eastern routes are serviced at London.

A typical electronic overhaul procedure is scarcely what could be called a "check". It is a thoroughly organized,

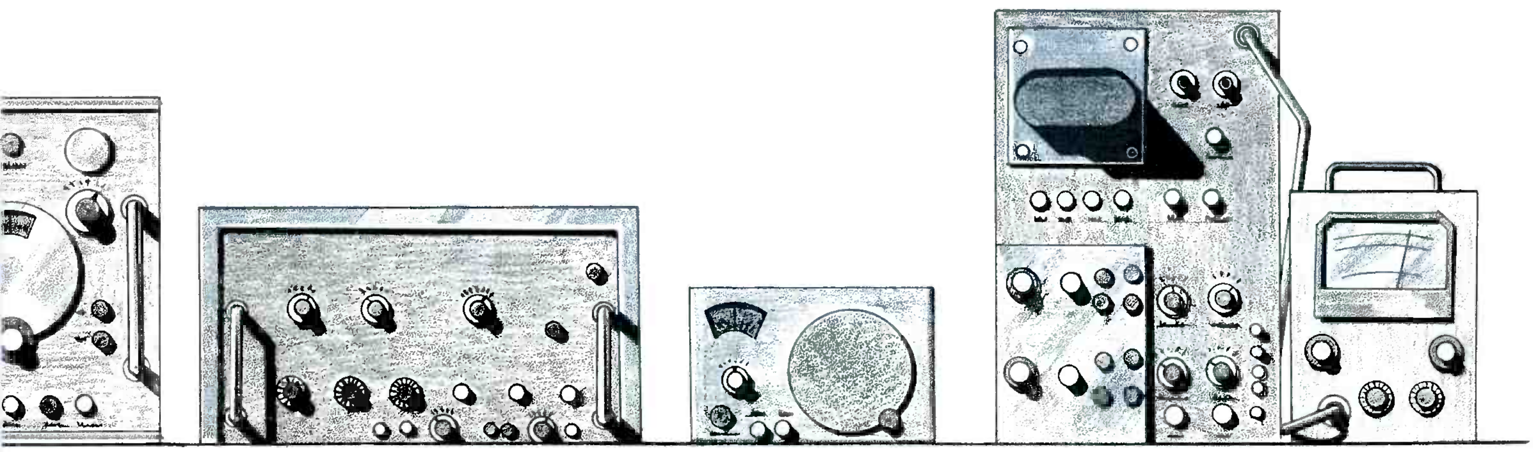


A detailed view of the Maintenance Bench

detailed, positively monitored and supervised examination. It is executed by a trained and licensed radio mechanic schooled as well, on the particular equipments for which he is responsible, in the classrooms of the electronics manufacturer. (No longer does a finger on an input lead serve suitably as a 60 cycle signal generator; and a fluorescent lamp has become a dubious device as an rf null indicator. But such is to be expected in a day when a DME, for example, can say more during a single dot of the Morse code than Mr. Morse could have said in five minutes, had his sending key remained intact.)

To provide some insight into the detailed thoroughness with which a modern electronics shop performs its duty the procedures followed in the overhaul of the Transponder and the DME are reviewed below. A complete set of test equipment is provided for each overhaul procedure. As many as eighteen units are associated with the Transponder tests; and, although this number represents alternate test gear configurations, the radio mechanic must know all the equipment. Typically, for a Transponder examination, the following would be employed:

A. Tektronix Scope, Model 535.
B. Hewlett-Packard 614 Signal Generator (2 required).
C. Beckman Berkeley Double Pulse Generator (2 required).
D. Narda Echo Box.
E. Dual Directional Coupler, H-P, Model 766D.
F. Termaline Coaxial Resistor, Bird Electronics Corp., Model 81.
G. Thermistor Mount, H-P, Model 477B.



H. Rada Sweep, Kay Electric.

I. Microlab XP-6 L-Band Detector.

J. General Radio Co., 50 ohm load, Type 874.

K. Weston Analyzer Multitester.

L. Pan American Design Test Panel with AC and DC Voltmeters and Variac.

M. Mixer Pad.

N. Isolation Resistors.

O. Beckman Frequency Counter.

Transponder Examination

It should be noted that although what follows is not the actual plan used by the electronics shop, it is a close approximation to it and includes all major steps.

Preliminary

1. General inspection of unit to reveal loose connections, corrosion, dirt, etc.; examination of fuses and holders, wiring and insulation, capacitors (for leaks and bulges); and tubes, for microphonics.

2. Set up test equipment.

Test 1 Receiver Pulse Output

With the Transponder interconnected to the proper test equipment it is initially checked for proper output pulse amplitude against an input signal of —74 dbm. The receiver output pulse is further monitored in 9 dbm steps throughout a —74 dbm to —20 dbm range to make sure that the lin/log detector does not distort or overload causing amplitude distortion (which would vary the original relation between the two input pulses).

Test 2 Receiver Sensitivity

Tested at an interrogation rate of 1000 pps the receiver should produce 50% replies at a —74 dbm input. Gain is then reduced by 12 dbm and sensitivity rechecked on a higher input level. This is done to make sure that the receiver will not overload in the presence of strong signals (i.e., when it is close to a station).

Test 3 The Decoder

Test equipment is set up for a two-pulse check with attention being given to pulse spacing and pulse width while pulse amplitude is varied. A three-step procedure (specified input; proper pulse-to-pulse relation; specified replies at specified pulse relation) is repeated through 6 steps from high to low input. This test assures that the two-pulse sidelobe suppression circuitry is operating properly. A similar three-pulse check follows.

Test 4 Identification Time Delay Test

This test is performed to ascertain the proper functioning of the IDENT Switch (the switch used by the pilot to acknowledge the radar ground controller's request for aircraft identification). The identification pulse must appear in the reply code for 15 seconds and must be removed (automatically) at the end of this period.

Test 5 Suppression Pulse

Suppression pulses are generated within the transponder and are used to suppress other pulsed radar systems or units within the transponder's frequency range, while the transponder is transmitting; pulses are used to suppress the transponder's own receiver during transponder transmissions.

Test 6 Automatic Output & Countdown

This test is made to insure that the transponder will provide fewer than 90% replies at signal levels down to a specified point; the test is made at an interrogation rate of 2400 pulses per second. A "countdown" circuit (similar to an AGC) is used in the transponder to prevent overloading of the modulator and transmitting tubes (i.e., to prevent exceeding their duty cycle). The countdown circuit acts to reduce transponder replies as inquiries increase beyond a certain limit. The countdown test monitors this circuitry.

Test 7 Reply Frequency Test

This test is made to ascertain that the transponder is replying on the correct frequency. Transmitter output frequency, monitored by an echo box, must be accurate to within ± 2 tenths of one percent at 1090 mc.

Test 8 Transmitter Power Output Test

In this test the unit is monitored with an incoming signal set just below the minimum triggering level. A minimum output of .5 kw must be obtained; if not, the unit is shut down and adjustments are made to achieve proper power. Sustained, reliable life is sought from the power or transmitting tubes. Machlett planar triodes fulfill these requirements.

Test 9 Transmitter Pulse Characteristics Test

After it has been established that the proper pulses are displayed for the proper code setting of the Transponder Reply Code Selector the pulse width, pulse rise time, and pulse decay time of the first and last reply pulses (framing pulses) are recorded. Adjustments are made as required to obtain proper pulse characteristics, not only for the framing pulses, but for all other pulses as well.

Test 10 Ringing Oscillator Frequency Adjustment

First the spacing between framing pulses is established. Next the spacing of the pulses between the framing pulses is established. In-between spacing time is 2.9 usec; overall time, between the first framing pulse and the Identification pulse which follows *must* be a tight 24.65, ± .1 usec. The unit has now been readied for flight. It is given a new rotation schedule date and is fed into the "pipe line" to await installation. Scheduled time to overhaul the Transponder is approximately six and one-half hours.

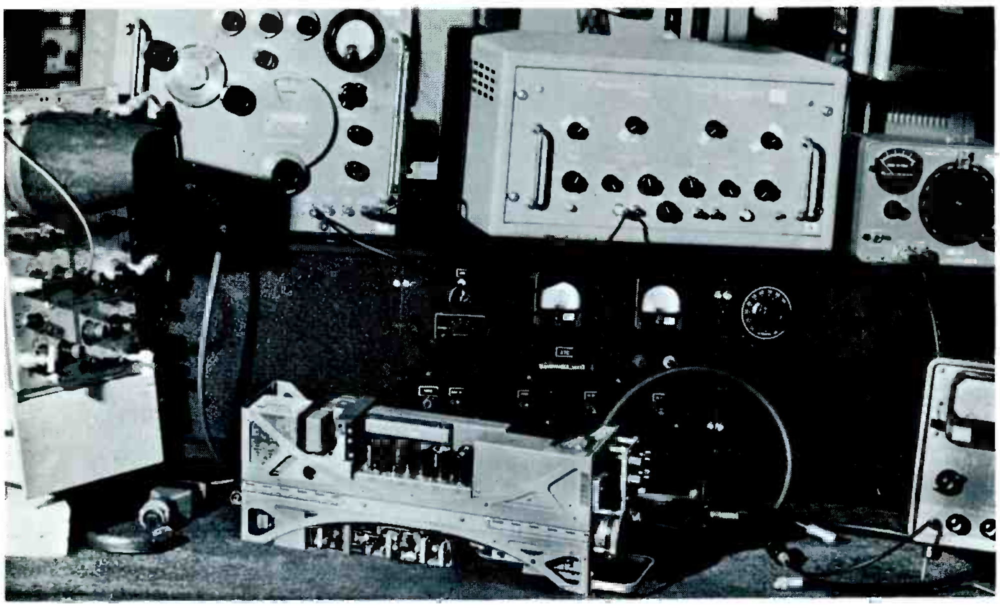


Figure 1 — A Federal ITT DME 100A, is shown with modulator card removed. The final output tube position (see just above the right hand of the Master Mechanic) is readied for a check of the ML-7815. Machlett planar triodes at Pan American have shown a very low removal rate.

The DME

Somewhat more complex than the Transponder the DME requires more extensive test gear for its evaluation. Whereas ten basic units were required for the Transponder, twenty-four are required for the DME, including such possibly unexpected items as a stop watch, swamping tool and a torque wrench. More usual are: Frequency Counter, Audio Oscillator, audio output meter, DC and AC VTVM's, UHF Signal Generator, dual trace oscilloscope, slotted line and two special units, the 578D-1 DME Test Set and the 235A Navigation Aids Test Set. The remainder of the items include such pieces as signal injection probe, test cables and special adjusting tools.

After preliminaries, as indicated in the Transponder tests, (but including more complicated mechanical inspection; e.g., checking of auto positioner clutch torques), the DME is tested for its ability to track, to measure elapsed time between its interrogation and ground return reply pulses and to convert the latter information into a digital readout (i.e., miles from a station).

Test 1 Time Delay

A time delay is employed to permit output tubes to warm up prior to operation.

Test 2 AGC Adjustment

Automatic Gain Control is set at a high squitter* rate using the AGC voltage at the decoder module.

*Squitter or fill-in pulses are used by the ground station to maintain a constant duty cycle during periods of varying interrogations. Squitter pulses are random spaced pulse pairs.

Test 3 Transmitter Frequency

The DME is operated on 126 different channels; these are tested throughout the entire range. The output frequency must be maintained within .007% of the assigned frequency.

Test 4 Power Output

Measured across the DME spectrum on 126 channels, the peak power output of the first and second transmitted pulses is measured. Output should not be less than 28 dbw (630 watts) and must not vary more than 1 db between pulses.

Test 5 Transmitter Pulse Characteristics

Rise and fall times of the first and second transmitted pulses is measured to be within 3 usec; pulse width characteristics are measured and pulse shapes observed. This test is repeated at the mid and at the high end of the band. To establish the pulse width, the 50% voltage point of the leading edge of the first transmitted pulse is measured with reference to the trailing edge of the same pulse.

Test 6 Receiver Sensitivity

The DME is adjusted so that it operates properly at a sensitivity of —90 dbm. Twelve channels across the band are then checked for sensitivity.

Test 7 Receiver Decoder Selectivity

With the antenna jack connected to the rf jack of the Navigation Aids Test Set (which, although it has not been so mentioned, has been used extensively in previous tests), a signal at an extremely low level is fed to the DME Receiver. The receiver is then checked for its ability to search, lock on and track.

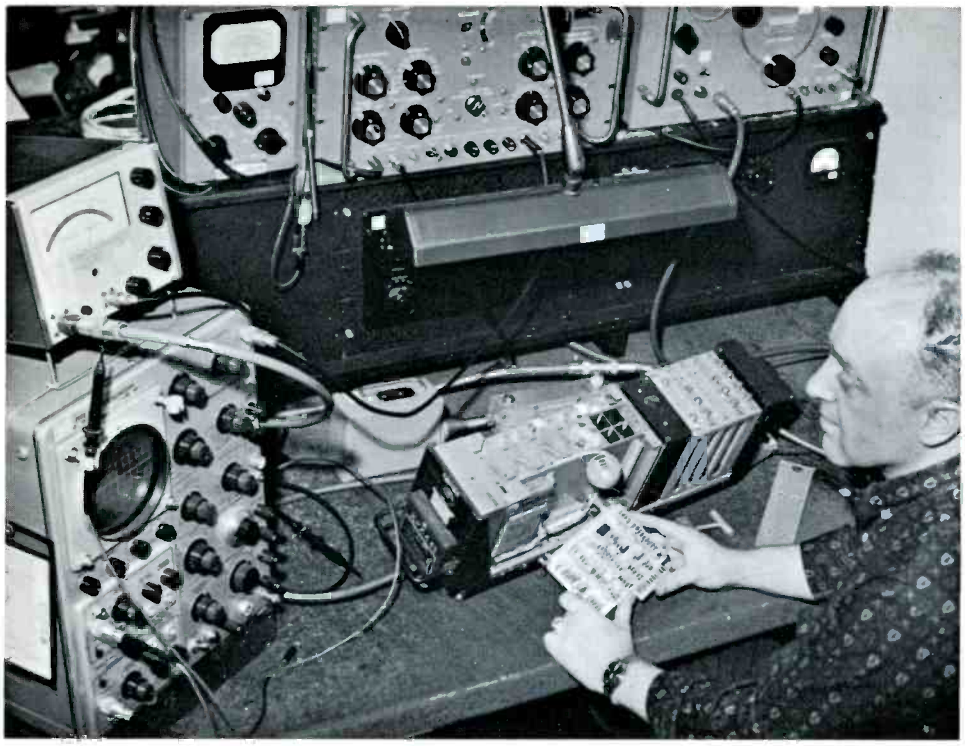


Figure 2 — Video output, taken from the video amplifier, and shown on the scope, left, provides a two pulse waveform with a 12 usec spacing for a given rf. The detected video pulses must attain a specified amplitude — thus indicating proper receiver sensitivity.

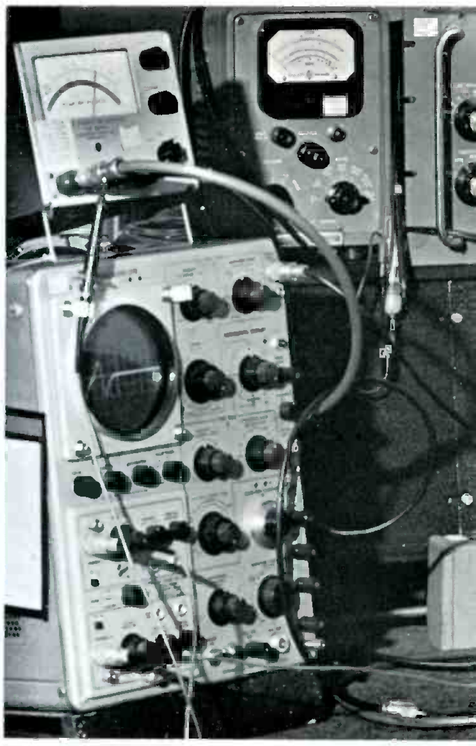


Figure 3 — A Wilcox 714B Transponder undergoes a bench check. These units were recently modified to provide two and three pulse sidelobe suppression.

Test 8 Interrogation Pulse Repetition Rate

Connected to a frequency counter, and with the Distance switch set nearly to the maximum range, the pulse repetition frequency is measured while the DME is searching. The search rate of 145 ± 2 pulse pairs, as averaged over 10 seconds, should be recorded. With the unit set to close range similar measurements are made, with the prf being reduced to approximately 30 pulses per second (or the prf used during track). Pulses are also checked for irregularity of spacing, this being a necessary condition.

Test 9 Search Limit

A short-range search mode is used when the aircraft is within 50 miles of an airport VORTAC station. Channels 17 to 56 are associated with this mode and are usually paired with the VOR which provides the proper bearing for approach to the airport.

An over-ride switch permits the pilot to search beyond the 50 mile range when he is operating on Channels 17 through 56.

With the DME test set adjusted to a low-number channel and suitably connected to the DME, observation is made to determine that the DME transmits only between zero range and middle-close range (50 miles). This procedure is checked on four channel positions.

Test 10 Distance Accuracy

The DME unit is compared to the DME test set and adjusted as required to be certain that the distance module reading is accurate; i.e., that the read-out number corresponds to the proper distance.

Test 11 Distance Module Adjustments

The distance module is basic to the DME; it provides the primary frequency on which all mileage measurements are based.

The distance module test involves three separate sections:

a) check to determine that the suppression pulses are satisfactory.

b) check to determine that the prf has the necessary random characteristic or "jitter". Jitter is needed to provide a unique signature for each DME and to assure that a DME will read back only its own transmitted pulses. If this provision were not made one aircraft could read another and achieve unreliable data—to say the least.

c) check to determine that the DME will provide mileage readings accurate to within ± .2 miles. This is done by adjusting the distance module to a prf of

Figure 4 — Two day's incoming equipments line the first four bins; outgoing, plastic bagged, serviceable, units are on the right. The apparent discrepancy in in-versus-out is accounted for by the fact that serviced units are picked up four times a day.

145 ± 2 pulse pairs (as averaged over 10 seconds) then adjusting the Phantastron gate width so that as the search out to maximum occurs the square wave pulse width (controlled by the Phantastron) increases and maintains a proper relation to distance sine wave. The trailing edge of the Phantastron pulse must always occur midway between the positive peak and negative going zero crossing of the sine wave.

Test 12 Tracking Characteristics and Tracking Error

The DME must track properly at its maximum distance or conversely at minimum signal input. Tests are made to determine that the DME will search, lock on and track from a signal level starting at —90 dbm.

Test 13 Prememory and Memory Test

A DME must "remember" a signal input for a brief time period to accommodate occasions when, for example, the aircraft attitude might not permit reception of a station. During the memory interval, the red flag appears on the distance indicator partially obscuring the reading shown and indicating that it is not to be used. Prior to this, however, or during the prememory period the indicator will stop turning for a period of 4 to 8 seconds; if the signal is found during that time the unit will then continue. If the signal is not found the flag appears and remains for 7 to 11 seconds. Once again, if the signal is found the flag will drop, the unit will "catch-up" and continue to track. Or, if the signal has been lost the unit will begin to search.

Test 14 Search Time

In this test the unit is adjusted so that it will search throughout its entire range, 0 to 200 miles in no more than 20 seconds.

Test 15 Identification Tone Output

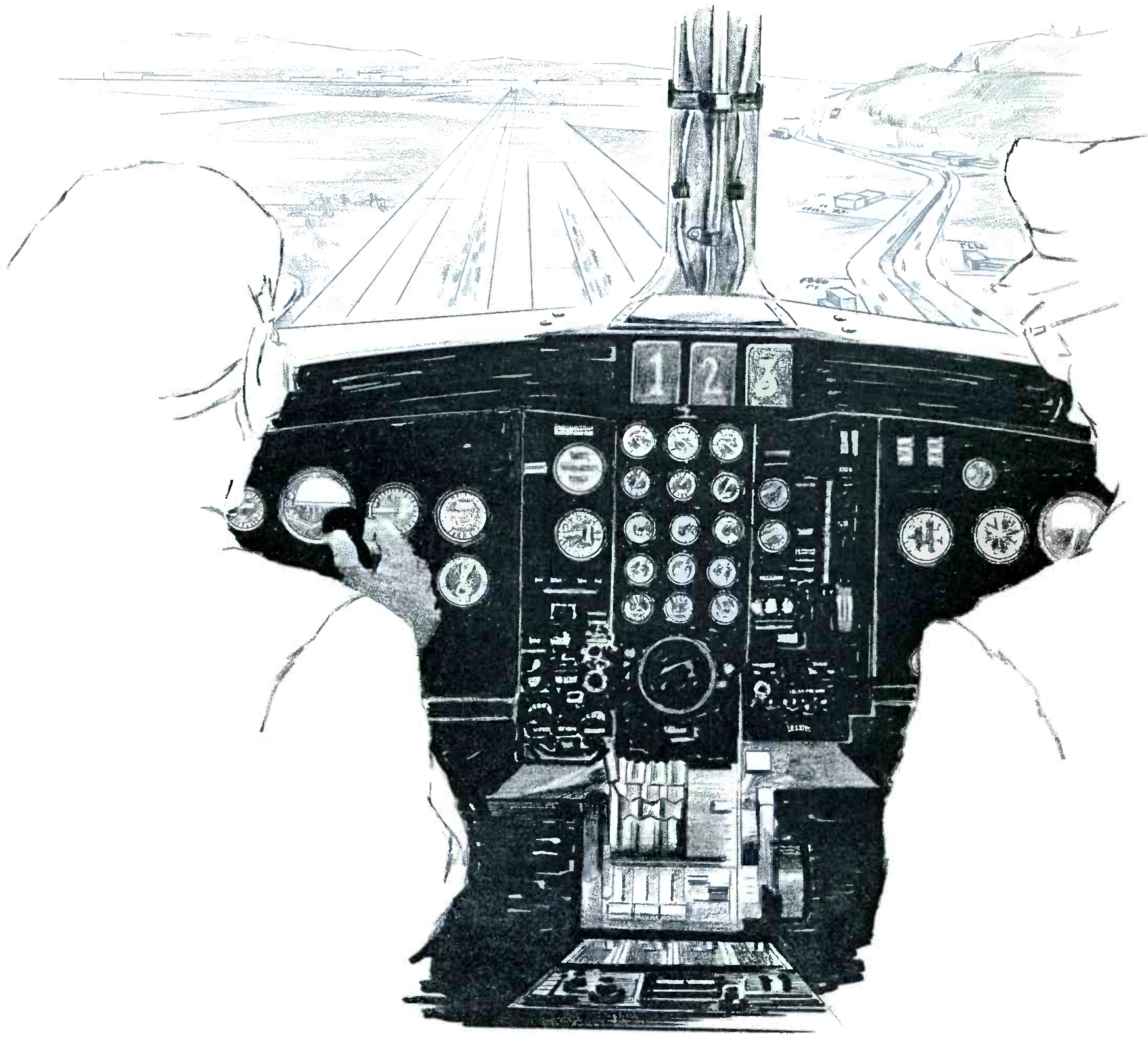
Adjustment for the proper tone output signal to the headsets. The signal referred to comes from the ground station which identifies itself by Morse Code and by tone every 35 seconds.

Test 16 Suppression Pulse Input Test

Pulse suppression is required during transmission from the transponder or DME to prevent receiver overload. Suppression of the incoming video pulse requires adjustment of the suppression pulse and video pulse; the suppression pulse amplitude must be of a specified size. These factors are determined by this test.

Wrapped neatly in its polyethylene sack, properly tagged and with a new date card, the DME awaits flight use. Time for overhaul, approximately eight hours.

American Airlines: A review of a major



Editor's Note:

American Airlines is a major domestic carrier of air passengers and air cargo. It operates a fleet of 171 airplanes (76 fanjets, 24 turboprop Electras, 71 piston planes) to 50 cities in 21 states in the U. S., Canada and Mexico. In 1963 American carried 9,124,000 passengers and flew 7,205,474,757 revenue passenger miles and 210,791,670 ton miles of air cargo. American has on order for delivery in the 1964-65-66 period, 34 more subsonic jets (19 three-engine and 15 two-engine types). American has also reserved delivery positions for 12 supersonic transports, 6 of the U. S. version and 6 of the British-French type.

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H. Heyer, General Foreman, Field Electronics Repair Shop

network of Field Electronic Repair Shops

A major airline system must provide a major network of maintenance bases. To take advantage of climate and the unusual mobility of their "product" many such bases are located in warmer areas away from traffic centers. Here the "barn" doors may be open most of the time and here the large scale work — airframe overhaul — is performed. However, a combination of traffic density, inventory maintenance level, and item availability sometimes dictate the need for maintenance base stations located near major terminal areas. Such is the case, for example, with the Field Electronic Repair Shops operated by American Airlines.

This system of Base stations comprises — in conjunction with line maintenance — the first line of defense in the maintenance program. Five such units are operated by American (See Figure 1) at New York (LaGuardia); New York (J. F. K. International); Chicago (O'Hare); Dallas (Love Field); and Los Angeles (Los Angeles Municipal). These shops, in turn, act as a center for area maintenance as shown in the figure just noted. An inventory of spares is provided at each of these five stations as well as at the "feeder stations" shown in Figure 1.

It must be apparent that in any endeavor so thoroughly organized and so thoroughly committed to operate in a specific, legally sanctioned way — as are the airlines — that an electronic shop must be more than a group of electronic technicians or line shop mechanics, as they are known in the industry. Such is, of course, the case.

Beginning, first, with what might be termed the "charter" of the Field Electronic Repair Shop, it is, in accordance with this document, authorized to perform certain specific repairs. These repairs are to be done only by FAA certificated mechanics operating in an FAA certificated shop. In the Shop station repairs are restricted to tube replacement, fixing broken wires, replacing resistors, and to the determination of whether or not a given unit does or does not meet satisfactory operating criteria. These criteria are determined by reference to the Field Electronic Repair Manual which closely defines the checks which may be made. The checks themselves are performed in accordance with individual repair manuals describing a given equipment. A repair manual is prepared by the airline using the vendor's material and is submitted to the FAA for approval of procedure and accuracy. Not until this legal sanction has been given may the manual be used. It may be assumed that changes of its contents are not lightly made since each change would, again, require approval. In this manner a continuity of discipline and high standard of performance is established.

To place the American Airlines' line shop maintenance operation in perspective, it will be well to outline the general program of which it is a part, a maintenance practice known as "Progressive Maintenance." Although the final goal of this program for all aircraft items is "On Condition Status" (in which a piece of equipment, in theory, could never receive a major overhaul, being kept in proper trim by the repeated shop maintenance reviews) this ultimate ideal has not been reached. Progressive Maintenance, is, however, a major step in this direction and relies on the performance of as many maintenance services as possible—short of overhaul—on the aircraft, and the performance of these services primarily in terms of the operating conditions of the item. This is in sharp contrast to "calendar maintenance" in which, regardless of how well it was working, an item was removed and overhauled on a certain time schedule.

In the present system the aircraft is:

a) given a "walk-around" check on layover (every 4 to 6 hours approximately), at which time a visual of equipment security is made.
b) given a service check every 30 hours by line mechanics. (Electronic components, for example, are reviewed to see if their calendar "due dates" for overhaul have matured. Units are monitored for proper output, etc.)
c) given a systems check every 300 to 500 hours in which a mobile "test bench" is wheeled to the aircraft and all systems — electrical, hydraulic, electronic, and so forth — are examined. If everything is all right nothing is changed.

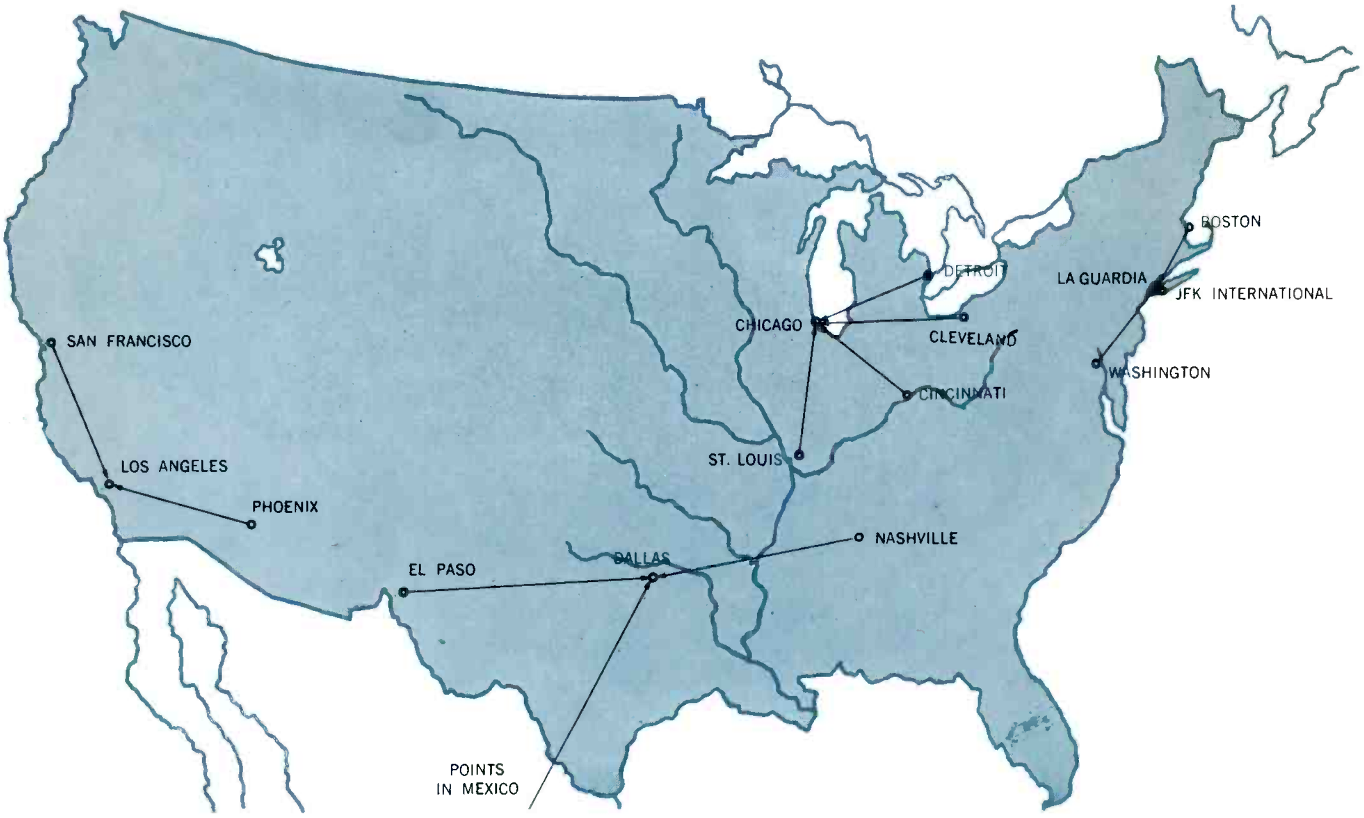


Figure 1 — American Airlines' Field Shop network: Los Angeles; Dallas; Chicago; and New York (two shops). Other points, such as Boston, are feeder shops sending equipment to the Field Shop. Electronic equipment not serviceable by the Field Shop goes to the Electronic Overhaul Shop at LaGuardia (New York).

d) given a base overhaul. (Primarily engines, airframe and cabin furnishings.)

The degree to which longer "on condition" periods in electronic equipment participates continues to grow. The primary change, reflected now in present practice, is found in less frequent removal for interim checks and on the greater reliance on localized or "on-the-aircraft" checks.

Returning now to the specific details of the line shop maintenance situation the usual sequence is as follows:

1. A line mechanic removes a unit on a Pilot complaint or as a result of finding a unit out of specification on the periodic 300 hour check.

2. The unit is reviewed by a line shop mechanic to determine if the complaint or "squawk" can be verified. If it can't be verified (as is frequently the case) and the unit meets operating specifications as defined by the Manual the unit is certified as Serviceable, and returned to inventory. (Note here that its "Service Date" or "zero time" is not thereby altered. The Service Date, found on small card mounted in front of a unit, is changed only after a main base overhaul.) Should the unit be found unserviceable it is, at the discretion of the Foreman of the Electronics Line Shop, repaired and verified as serviceable by the line shop mechanic responsible. His verification is, in turn, reviewed by a lead mechanic known as a Quality Control Designee. Finally, the unit is routed to stores.

An Instrument Panel 60′ x 60′

In a manner of speaking this is what a field shop might be called, for each of the electronic units associated with the instrument panel and pedestal are "mounted" on benches carrying specifically designed test equipment for a given unit (see Figure 2). Nearly all test panels are designed and built at American's main Electronics Overhaul Base at LaGuardia. (Some units, such as KIFIS, are purchased as are, of course, commercial test meters and specialized testers.)

A test panel is designed to accommodate only one type of unit — such as a DME or a VOR/ILS receiver — and provides, operating voltages, input signals and a suitable readout and calibrating device. Each test bench which is electrically isolated, carries power sources, paralleling those found on the aircraft. Power available is: 28 Vdc; 115v,

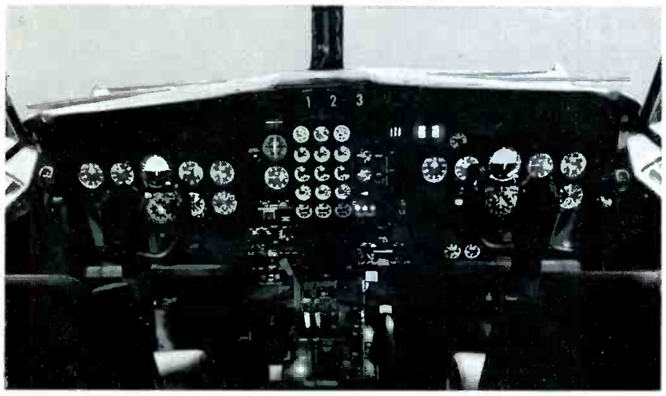
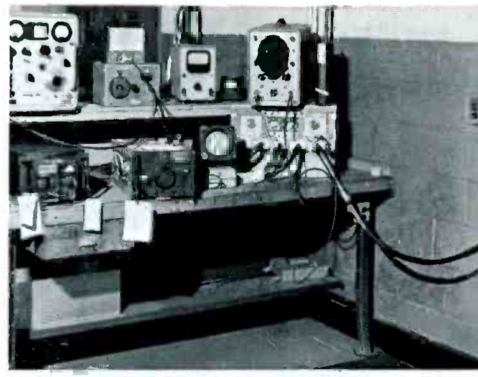


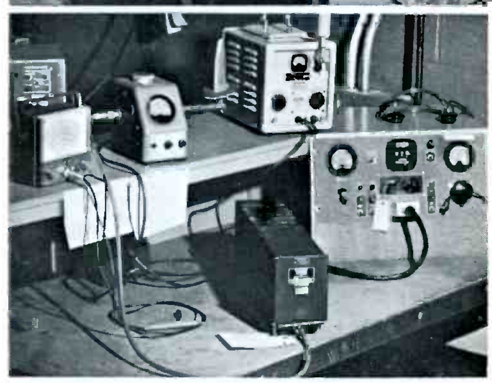
Figure 2 — Above the instrument panel of American Airlines' new 727 jet. To the right, sections of the "60'x 60' instrument panel" — which is, in actuality, a series of specialized test benches on which are laid out the various electronic instruments used by American's aircraft. . . . 2a AVQ 10 Weather Radar; 2b VOR/ILS Receiver; 2c DME; 2d Transponder; 2e KIFIS.

2A



2B

2C



2D

2E

400c, 3 Ø; and 115v, 60c, 1 Ø. Dry compressed air is available at each bench.

To assure the uniform performance of each of its five Line Shops all standards used for calibration, output or other measurements are maintained by a specialist from the LaGuardia overhaul base. Line Shop instruments are calibrated every 30 days against the base standards from LaGuardia.

Twelve Black Boxes and a Tape Recorder

Someday, perhaps, the equipment manufacturers may relent and furnish their units in colors more stimulating than black. Until that time, the term "black box" is necessarily appropriate — (even the Tape Recorder comes in a black box). This seemingly out of place unit, which serves to welcome aboard the passenger prior to his flight, is not on hand to entertain the busy line shop mechanics whose job it is, every so often, to change the tape. In the course of tape changing and the more serious business of calibration and repair, the Field Maintenance Shop at JFK handles approximately 300 units a month, achieving, typically, a 92% effectivity (or, in other words, forwarding to base overhaul only 8% of the incoming units).

Weather Radar

Search unit for safe flight, airborne weather radar provides a display of precipitation areas which may lie in the flight path. The radar return indicates the storm cells and thus allows the pilot to avoid them and fly through the calm areas of the cloud system.

Shown here (Figure 2a) is the C-Band AVQ-10 radar ready for a bench check. AVQ-10 with a peak power of 75kw sweeps out ranges of 20, 50, and 150 miles.

The JFK line shop replaces sub-assemblies as required, services all tubes (except the magnetron), and makes general repairs. Conditions diagnosed as outside the province of the line shop are referred to Tulsa.

A Bench test unit for the smaller AVQ-50 radar is also provided.

VOR/ILS Receiver

Since 1946 when the first VOR systems were installed the VOR-VHF Omnidirectional Radio range has been a major element in the FAA "navaid" or navigational aid program. VOR was coupled with TACAN (as described elsewhere in this issue) in 1958 to produce VORTAC, now the primary navigational system for commercial airlines — and a growing system general aviation.

A VOR station, operating on frequencies between 108 and 118 mc, provides a 360° "spoked" wheel giving an azimuth information to the pilot. Each spoke or radial, separated by 1°, is indicated on bearing selector on the aircraft's instrument panel; other indicators provide on-bearing or off-bearing information and to-or-from the station data.

Using a VOR* bearing a pilot may fly an accurate course heading, may establish ground speed by noting time between radials (as he flies on a course perpendicular to the radial), may establish a fix or series of fixes using two or more of the 700 plus VOR stations now in use.

With the equipment here, as with the similar units used by commercial airlines, the VOR receiver has associated with it an ILS — Instrument Landing System — section used after the plane has approached the terminal area and is established in the traffic pattern.

Shown here (Figure 2b) is the test equipment associated with the VOR/ILS receiver. At the left, signal generator (power supply not shown), next an ac voltmeter; top right a commercial unit providing omnirange and localizer simulated signals: middle, right, power supply; bottom, right, a panel designed and built by American Airlines at LaGuardia. This panel displays: receiver signal output; glide path deviation and localizer, or range deviation, output (readout unit, top row of instruments, second from left); omnirange course information — given in ua; bearing indicator; and a to-from indicator. On the bench is the unit under test.

Marker Receiver

Closely related to the ILS equipment, just noted, is a highly selective receiver tuned only to the 75 mc marker beacon signal. As the aircraft descends on the glide slope toward the runway it passes over an outer and then a middle marker beacon. These are narrow, highly directional beams (in the vertical), which cause signal lights (first purple, then amber) to appear on the instrument panel as the aircraft passes over the beacons. Beacon position is specifically charted for every landing field runway and the pilot knows, for example, that as he passes over the outer marker beacon he is 5 miles from the end of the runway, and next, when the amber beacon signal appears, that he is 3500 feet from the end of the runway. The runway approach lights lead in from this point. (The marker receiver bench is not illustrated.)

Glide Slope Receivers

Glide slope information, transmitted in the 328.6 to 335.4 frequency range, is originated from an antenna located on the center line of the runway and is normally under the 50 to 1 clearance plane. Glide slope angle is established between 2½ and 3 degrees depending on the terrain. Glide slope reference is maintained in cockpit by means of the glide slope needle on an indicator (as shown on the test panel, Figure 2b).

Communications

VHF Receiver — VHF Transmitter

Air to ground voice communications is an essential part of the operation of the commercial aircraft. Because of the basic importance of voice communications the commercial aircraft maintain a VHF transmitter and receiver* for use at all times to talk with the en route FAA controller or with the air line's own communications network.

Similar to the transition from 200-400 mc airways "beams" to the VOR radials has been the change from HF to VHF in communications equipment. VHF has eliminated the effects of variable propagation characteristics (the right frequency had to be "matched" to existing atmospheric conditions for best reception; but this was not always possible and added complications in any event). VHF provides positive communications but limits propagation to line-of-sight, hence requiring more ground stations than HF for adequate coverage.

Designed to tune in 50 kc increments over the band from 118.0 mc to 135.95 mc the VHF transmitter is checked for accuracy of carrier frequency (.01%) and power output (25 watts). The VHF receiver is checked for sensitivity and alignment as well as proper frequency selection. Transmitters are checked for proper modulation and sidetone. (The Communications Bench is not illustrated.)

*VOR has superseded the LF/MF or A/N four quadrant range system which supplied the "beam" for navigators and pilots up through WW II and which is now in the process of being largely phased out. Relying on aural indications for to-from (station) and on-off (course), subject to static and fading, severely limited in numbers of channels and accuracy of "beams," the old low frequency system is entirely inadequate for modern high speed, high density navigation.

*There are two VHF communication systems on each aircraft. And two VOR systems that could be used as auxiliary receivers on the communications band.

ADF — Automatic Direction Finder

Originally associated with the LF/MF "beam" airways the ADF was used to provide radio fixes or, if necessary, to "home" on known radio stations. Covering a band from 100 to 1700 kcs this permitted, and still permits, the pilot to use, for example, commercial AM transmitters as powerful homing devices. However, ADF is relatively slow, and somewhat less accurate than VOR and also requires that the pilot generate his own To/From reference. ADF is now a back-up system (except for those areas outside United States and Europe where VOR systems do not exist).

The active element for the ADF is a rotatable loop antenna automatically tuned or positioned with to face to the desired station. It provides a "radio compass" readout on the instrument panel. Unlike the VOR reading magnetic variation is not accounted for and must be included as a correction. (The ADF test bench is not illustrated.) The Automatic Direction Finder is checked for sensitivity; antenna and loop position; dial accuracy (e.g., that the dial reads 200 kc on 200 kc); and azimuth accuracy.

DME

A DME is set up as shown (Figure 2c and Figure 3), connected to the 28 Vdc and 115 V 400 Cac supplies. Output pulse power (1 kw to 3 kw) is verified. Set to a frequency at the low end of the band (117.1 mc) a unit is checked for search at 5 and at 100 miles; this step is repeated at the high end of the band, 134.6 mcs. For the final check the unit is connected to an outside antenna and operated, proper mileage readout on the indicator being the final criteria.

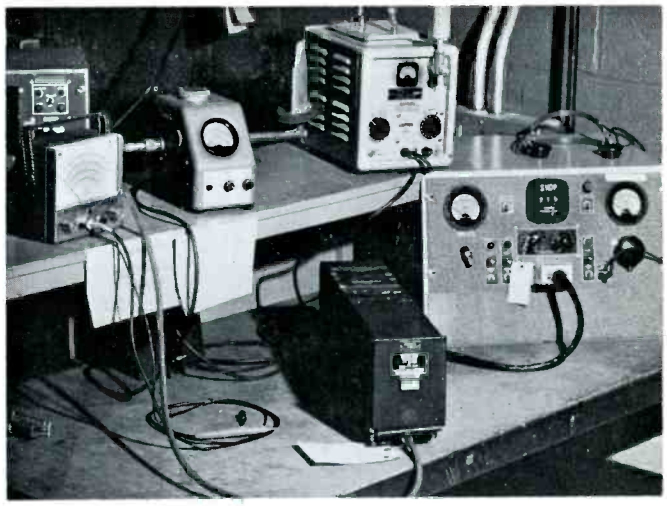
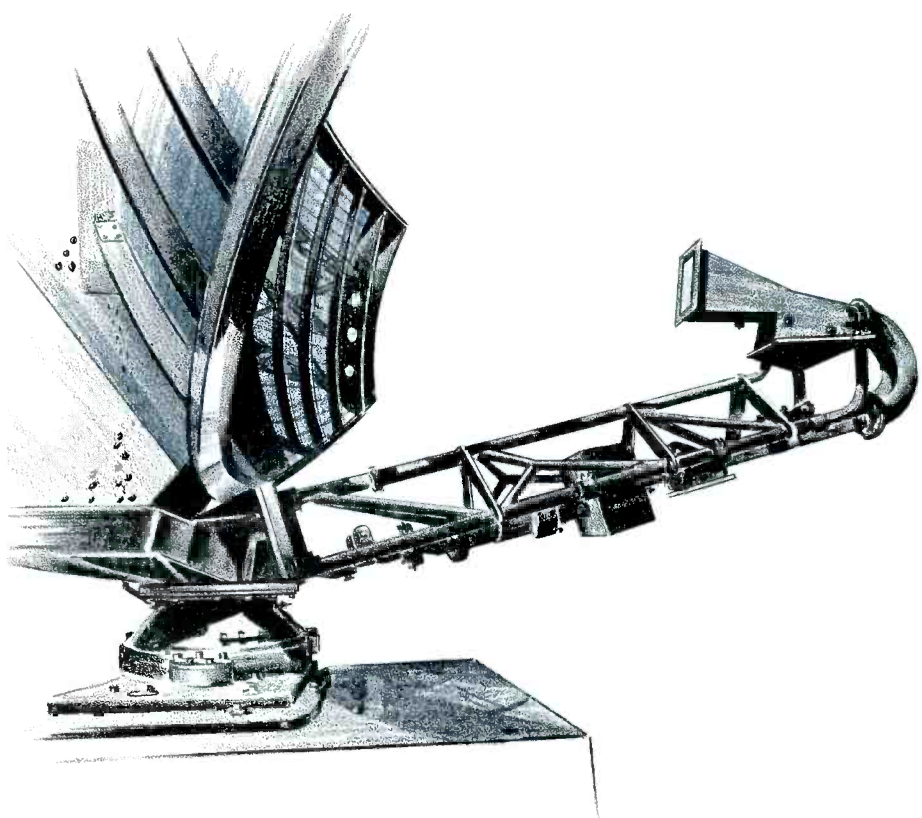


Figure 3 — DME Test Bench. The DME 100A and B (similar in external appearance to the unit shown) is now used extensively. The DME 100A or B is manufactured by Federal ITT.

The line station installs Machlett ML-7815 tubes as required. These output tubes are replaced one at a time until



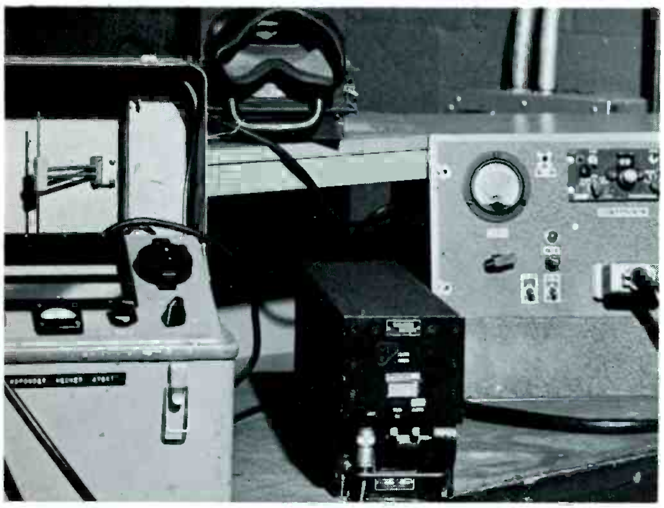


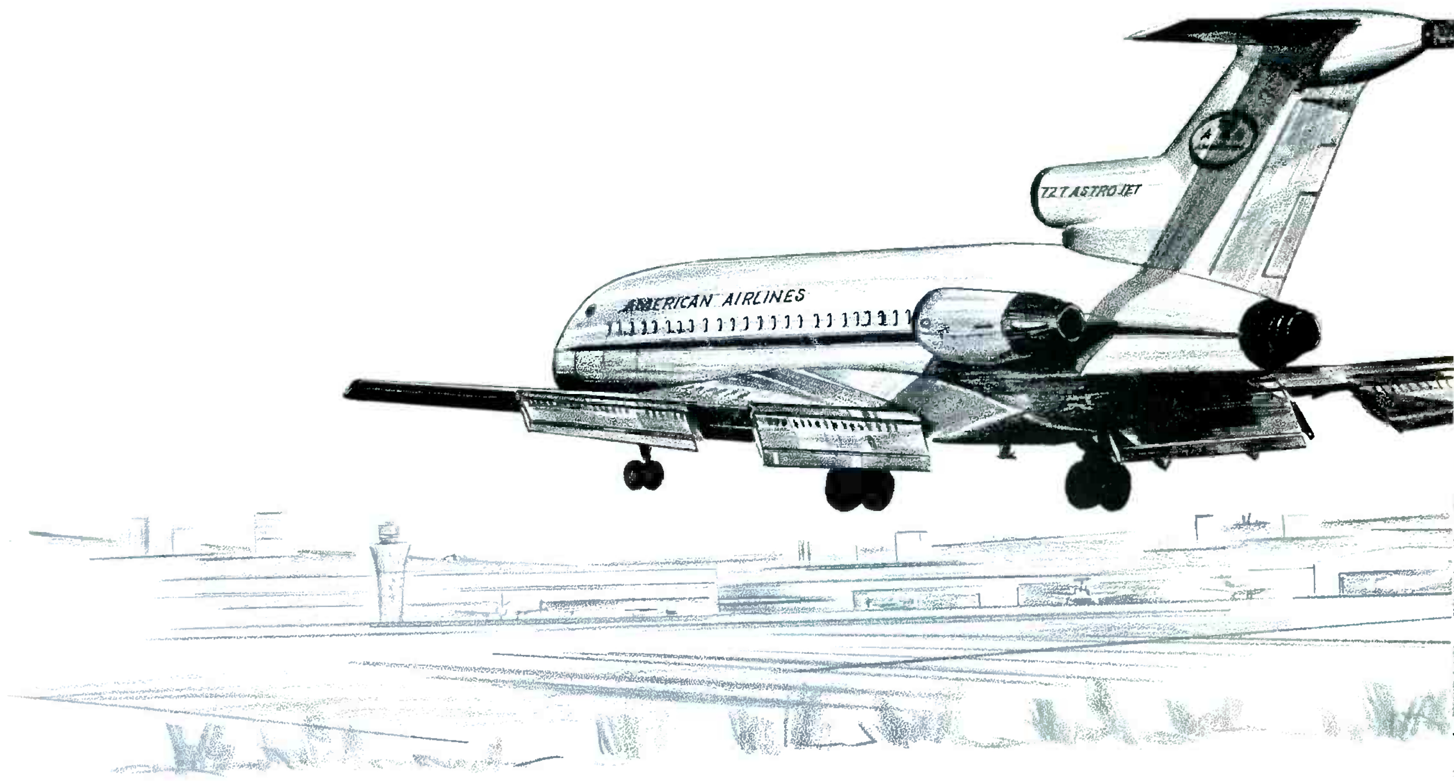
Figure 4 — Transponder Test Bench shown is the Collins transponder (Model No. 621A-2), bench and line check instrument and readout equipment.

required power is obtained.

For the purposes of the photograph the test units have been grouped in a manner which is not normal. For an actual test, the TACAN test set (manufactured by Federal ITT) is placed approximately 15 feet from the DME transmit-receive antenna (the blade seen in the upper center of the picture). The TACAN test unit is adjusted to transmit a certain mileage range and its output is fed to the DME 100A as shown. The TACAN test set provides both distance and bearing signals; the distance being read out on the range module of the test unit on the bench. Bearing signals are not used in the DMET system.

Transponder

The Transponder bench shows, from the left (Figure 4) a Transponder checker, Collins 576X-1, (used on the line, also), an oscilloscope, a Transponder and a test panel providing for mode and code selection. Briefly, the Transponder (Collins 621A-2) is examined for: power output (a minimum of 500 watts); receiver sensitivity (—72db); and mode selection.



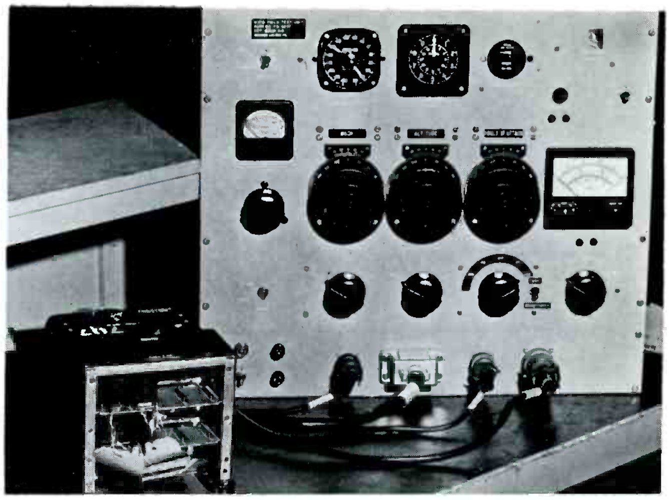


Figure 5 — KIFIS test unit, KIFIS at left, readout equipment at right. The KIFIS system provides accurate instrumentation data for the pilot.

KIFIS

KIFIS (Figure 5) is the name of an integrated flight system (manufactured by Kollsman Instrument Corporation) which presents to the cockpit flight readings which are continuously calibrated, corrected and/or inter-related as the case may be. A control chassis, shown, left in Figure 5, contains the matchbox size computers which perform the integrating operations.

Basically the KIFIS presents:

a) a reading for Airspeed/Angle of Attack*

b) a Machmeter

c) an Altimeter

d) True Air Speed (Airspeed vs. altitude vs. temperature)

e) Static Air Temperature.

*This instrument dial (not shown in the photograph) uses two pointers (one checkered, one plain) and an "angle of attack" segment indicator. The checkered pointer indicates maximum allowable airspeed (a modern version of the "red line" speed beyond which the aircraft may not go) corresponding for variations of altitude and temperature. As the aircraft climbs beyond 23,000 feet the maximum IAS (indicated airspeed) must decrease to keep the plane within proper Mach limits. The second pointer shows IAS. The angle-of-attack segment receives information from the angle of attack sensor; this data is integrated with pitot pressure (or airspeed data). The angle of attack segment then follows the IAS pointer to show the optimum IAS range for a given angle of attack — or in other words, to show the optimum IAS during cruise, approach, climb-out and rotation (nose up on take-off).

Editor's Note:

Trans World Airlines is a major carrier flying 50,000 miles of domestic and international routes. It operates a fleet of 83 jet aircraft and 86 piston aircraft serving 87 cities in 13 countries. In 1963 TWA carried 6,836,000 passengers and 152,267,000 ton-miles of airfreight. TWA has ordered 10 of U.S. manufactured and 6 Concorde supersonic transport aircraft.

CATHODE PRESS acknowledges with pleasure the assistance given in the preparation of the following article by:

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New Directions

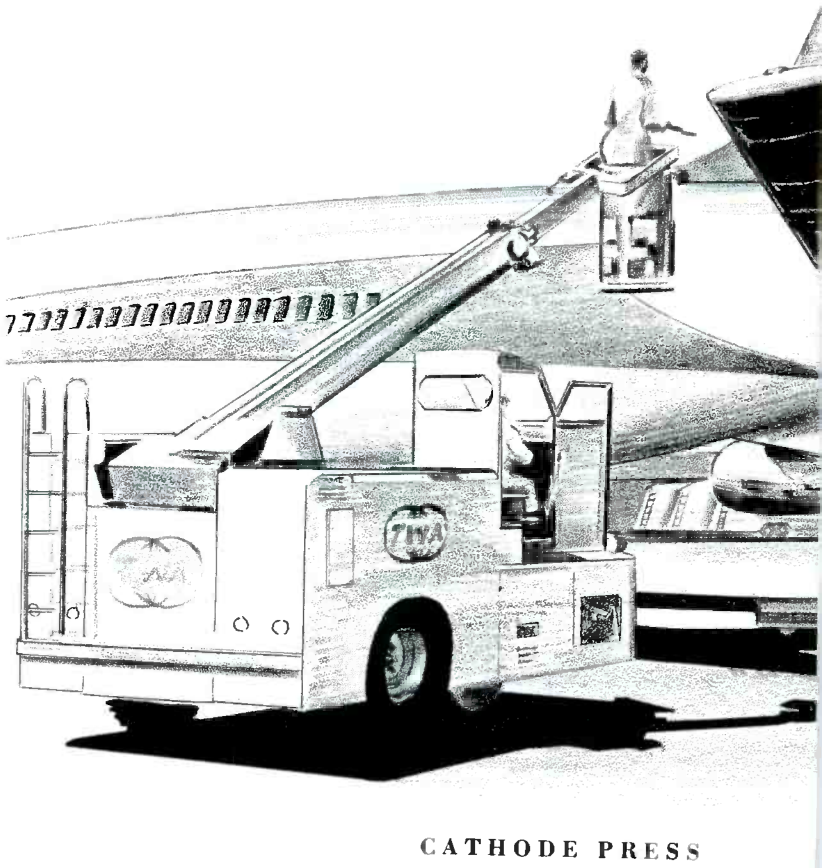
Trans World Airlines

Thirty years ago the railroad track was a useful part of a visual "coordinate system" used by the pilot-navigator. Today it is doubtful if he could even see the main line much of the time. Coupled with the virtual disappearance of visual reference, (even the clouds are watched with radar), the loss of physical reference (the stall warning computer has done much to replace the "seat of the pants") and the tremendously increased complexity of the aircraft — to say nothing of the need to make firm decisions well in advance of trouble (too late comes much sooner these days) — has been the explosive development and use of electronics. It may be fairly said that no other form of transportation (if we exclude space capsules*) would be so quickly crippled without its use.

Data prepared by the TWA engineering staff documents the foregoing in a striking way and shows a range of 440 to 7300% for increases relating to Number of Tubes and Semi-Conductor Devices to electronic equipment dollar value. (See Figures 1 to 4).

An obvious corollary to this situation is a heightened requirement for precise equipment maintenance. But, as in-

*It is apparent, too, that the space capsule does not even have a pre-electronic past; it was born full into the golden age and would be inconceivable without electronics.



in Maintenance Program — Trans World Airlines

dicated elsewhere in this issue, as well as here, large-scale equipment maintenance is not simply a matter of precise work on the bench. It is, indeed a matter of affecting the very structure of the airline operation, and is designed to keep equipments at work for periods of as long as can be established as statistically valid, and requires a very nearly superhuman sense of self-awareness.

Although a jet engine itself is four to eight times as reliable as the best piston engine, the overall "mechanical delay" rate of the jet aircraft is perceptibly higher. To keep this factor as close to the piston rate as possible (4% vs 2%) TWA, in keeping with other airlines, has engaged in programs which go directly into the actual design of the aircraft and its associated equipment. For a major trunk airline the cost and complexity of such a program is great. TWA, for one, has had to:

"1) Make organizational changes to arrange our 5400 "manyears" of technical talent into a staff which in some respects resemble the specialization of the medical field. Specialty Foremen in power plant, electrical and instruments, electronics, mechanical systems and structures handle the front line day-to-day problems. The second echelon, Maintenance Engineers in the same specialties coordinate the activities of the Specialty Foreman and disseminate the distilled knowledge gained from front line experience. Their concern includes development of quick fixes, frequently on a fleet basis. Backing up both of these echelons are specialized Systems Engineers concerned with the development and application of long term modifications to improve performance of systems, to facilitate maintenance or to extend service life of components.

2) Establish a central Maintenance Coordinator office (see figure 5) at our base (see figure 6) near Kansas City provided with a nationwide network of leased intercom-type telephone circuits for rapid communication with the various stations on our routes.

3) Accomplish over 20,000 manhours per airplane of modification effort. This is nearly two hours of modification effort for each hour of flight.

4) Make a spare parts investment exceeding $71,000,000 representing 20 per cent of our aircraft original cost. This, incidentally, has been held nearly 5 per cent below what would have been otherwise necessary through aggressive and judicious pursuit of parts pooling with other carriers.

5) Make a tooling and test equipment investment of $8,000,000. (See figures 7 and 8).

6) Provide initial and recurrent training in excess of 1,250,000 manhours, the equivalent of 400 man-

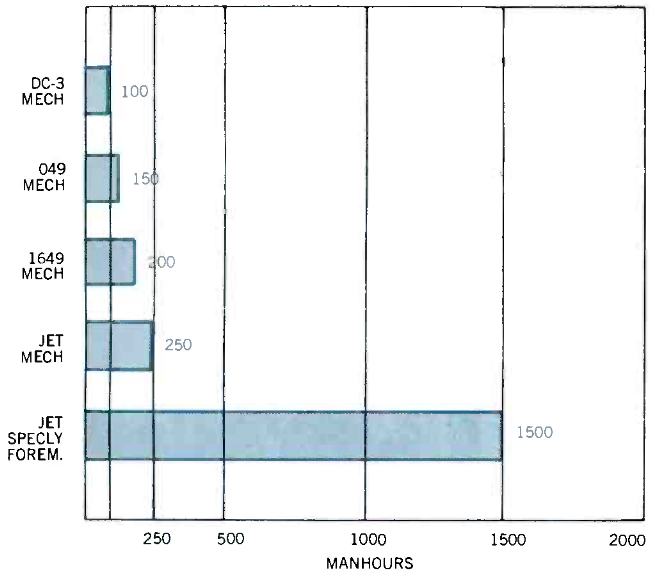


Figure 1 — Electronic Training Requirements.

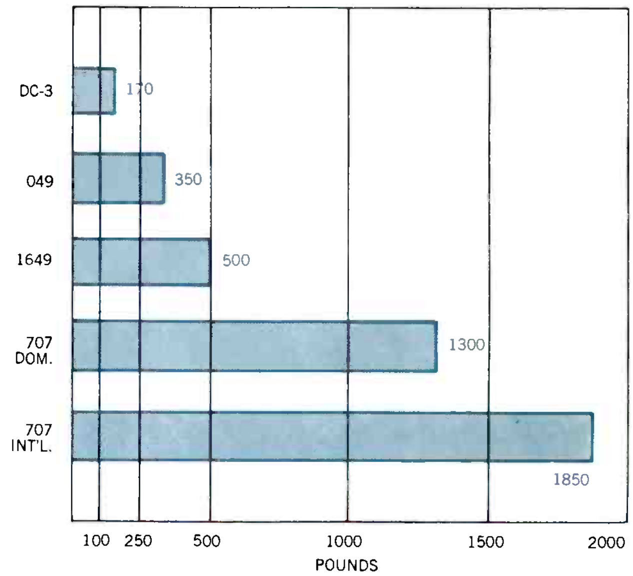


Figure 2 — Weight of Electronic Equipment.

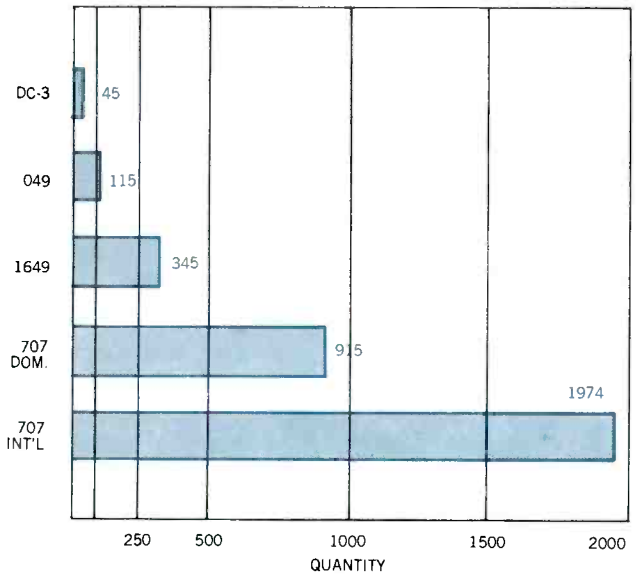


Figure 3 — Number of Tubes and Semi-Conductors Devices.

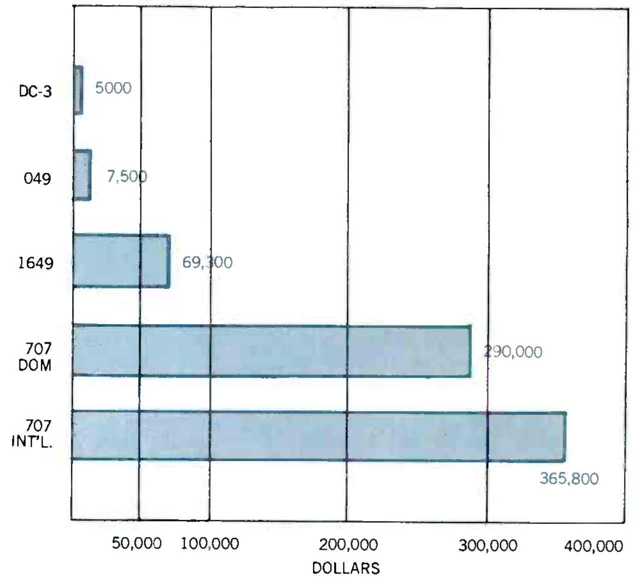


Figure 4 — Electronic Equipment Dollar Value.

hours per mechanic.

7) And most importantly, properly utilized the dedicated efforts of an experienced, well organized group of sensitive responsive people who can set winning strategy and quickly marshall the forces to achieve it."*

At 11:00 each morning

At precisely eleven o'clock each morning a group of ten to fifteen persons — each having specific responsibility for some section of TWA technical operations (as distinguished from marketing, finance, etc.) — meets to discuss and evaluate, in the manner of a post-graduate engineering seminar, the principal factors involved in delays of the day preceding. In a special room, (see figure 8) lit in a low key, with a podium for the speaker, microphones hanging from the ceiling, a large conference table — as well as chairs by the wall — the agenda is presented to the group. Surrounding them are ten sizeable bulletin boards, each with updated information on subjects such as Operational Performance, On Time Performance, Engine Time, Major Modification Status, aircraft comparisons, and Departure Delays Due to Maintenance.

Before each participant is a document (two, three or more pages) entitled

*From "Daily Sensitivity to Reliability", a paper prepared by B. M. Meador for presentation at the American Management Association Air Transport Conference.

"Trans World Airlines, Inc.
Operational Planning
Operational Planning Briefing and
Performance Resume
Issued . . .
Covering the period 0001-2400 local time . . . (date prior to issue date)"

Listed on Planning sheet is weather, both domestic and international.

For example:

International

February 25 — F-585-25 was setup over MIL due to rain and snow. Fog at LON resulted in the over weather operation of F702-25.

February 26 — Slack gradient over the United Kingdom France Germany with widespread low ceilings and fog causing LON and PAR to be marginal to below limits until 1000Z. A new Atlantic wave approaching the Iberian Peninsula will cause gusty surface winds at LIS.

"Activity Factors", Domestic is the next major listing. This includes "Mileage Performance" (scheduled miles, e.g., 302,171 miles flown and performance factor, e.g. 99.8); "Total Cancelled Miles" (cancelled departures and a breakdown of miles and flight sectors); "Origination Performance" (flight departure delays as grouped by number of minutes delayed); and "Termination Performance"

Figure 5 — Open for business 24 hours a day, seven days a week, the Maintenance Coordinator's office is in constant contact with the entire maintenance system, acting to correct immediate aircraft problems and coordinating action with the appropriate Engineering, Flight Operations or Administrative group as required to keep TWA flights on schedule.

Figure 6 — TWA's $25,000,000 overhaul and maintenance facility at Mid-Continent International airport at Kansas City, Mo., is pictured in this bird's eye view. Building at left foreground is the engine overhaul center, with its adjoining noise proof test cells. In upper center is the airframe overhaul building which has a center section for shops on the ground floor and offices on upper two floors.

Figure 7 — Ground time must be kept to a minimum to keep pace with the fast flight schedules of jet aircraft. Whether it be a routine de-icing job or repair of an antenna up at the top of the vertical fin, aircraft maintenance must be exacting and backed up by specialized equipment.

(arrival time vs scheduled time). A similar group of data is prepared for International Flights. The report also includes information on "Equipment" (engine changes; cylinder changes; fuel leaks; damage) and a section "Unusual Incidents — Preliminary Report". Here, for example, one finds such problems as loading delays, fuel pump malfunction, windshield crack, and so on.

Each participant having read his report, the briefing chairman, (using a telephone tie-in), then proceeds with a roll-call around the United States: Chicago, St. Louis, Kansas City, San Francisco, New York. Each person, Maintenance Director or Supervisor, is asked what his previous day's problems, if any, might have been. He reports and is questioned (via the ceiling mikes) by the expert member (or members) of the panel whose responsibility lies in the area of the difficulty. The discussion may be brief: "San Francisco reports no malfunctions or difficulties today"; or, for example, "New York reports a wing flap warning horn failed to turn off on Convair 880 — P8810 . . ." This, in turn, may start a discussion between New York, Kansas City and Chicago on the warning horn. The briefing system would, at that moment, be serving a major function by unifying otherwise isolated units of information, sensing and then defining a trend before it reaches a "noticeable" size. In other words, it is the function of this group to "notice" before anyone else — and they are equipped for this apparent clairvoyance by their individual expertise and by the immediate review of the entire operations system that their briefing provides. (We are pleased to note that, on the day that CATHODE PRESS was privileged to attend a session, no electronics equipment malfunction was listed by any reporting station. See figure 9).

The briefing session, proper, may last one half hour or more, but the ideas generated and the trends established and to be acted on, go far beyond this period. In fact, a form of centralized technical coordination is active 24 hours a day. The Maintenance Coordinator staffs a central office manned by specialized personnel; he accepts incoming teletype and telephone messages from the entire system and even, as required, from the flight captain or flight engineer during a flight. In addition, this office acts to correct immediate problems and perceives trends and coordinates action with the appropriate Engineering, Flight Operations, Technical Services or Administrative Group.

On Condition Maintenance

The Wonderful One Hoss Shay, with its extraordinary record for maintenance-free performance, has perhaps influenced too many of us. It is unfortunately apparent, for example, that many motorists continue to operate their vehicles long after even the most optimistic overhaul period

Figure 8 — At precisely eleven o'clock every morning this group from Technical Services Management at the Kansas City Overhaul Base review with the Maintenance Manager at all major maintenance stations the flight activities of the previous day to evaluate factors that have caused flight delays. This type of nation-wide conference is made possible by special telephone circuits connected to the microphones hanging from the ceiling.

has passed. But it is still a fact that "least maintenance" is the ideal goal. "On Condition" maintenance is the modern approach to this and is the answer in dynamic terms (as apposed to "static" or scheduled, periodic maintenance) to the question: How long may this equipment be safely operated before it needs repair or overhaul? TWA has inaugurated a program for providing an answer to this difficult question. Although the program now relates primarily to engine performance, aircraft structure, and electrical systems, it is planned in the future to apply it to the electronics equipment also. For this reason, but more because of the significant implications of this development, the "Airborne Performance Recorder" Program is reviewed below in some detail. (See figure 10).

TWA uses a recorder capable of monitoring 315 individual parameters; 207 are used in the present system, data being presented in analog form available for conversion to digital data for computer use.

In the present installation the recorder uses inputs from various existing sensors or transducers (used in conjunction with cockpit instrumentation) to obtain electrical signals for such factors as speed, positions, levels, temperatures, and pressures. As described* by B. M. Meador, Vice President, Engineering, Flight Test & Inspection, the current program "is directed toward establishing and developing:

1. Reliability of the recorder and sensing equipment.
2. Selecting and revising parameters as necessary to detect faults and equipment deterioration.
3. Development of the data processing programming which is necessary to handle the volume of recorded data.
4. Print out of data at line stations to be used as an aid for trouble correction.
5. Transmission of data from a line station to a central computer control point.
6. Transmission of data from the aircraft to ground for processing prior to flight termination.

All these steps must be evaluated prior to further consideration of equipment and methods for complete fleet installation.

Through proper system recording and data analysis we expect to be able to achieve "on-condition" maintenance. Our interpretation of "on-condition" maintenance is: To avoid the regular replacement of operating units so long as their performance is definitely above minimum established performance levels. This is quite different than the existing "time" control methods employed today. Time between overhauls is a very cautious and conservative limit placed on units and systems by statistical methods estab-

*From "Airborne Maintenance Recorder. A New Airline Tool" by B. M. Meador, a paper presented at the Aerospace and Navigational Electronics Conference, Baltimore, Maryland, October 21-23, 1963.

lished to avoid the consequences of a large number of failures. The penalty for this method of control is that many systems are removed with actually many more hours of good serviceable life remaining.

A more practical approach would be to know the actual state of health of a system at a frequent interval throughout its entire service life. This can be achieved through the use of an airborne recorder and proper utilization and analysis of the data acquired. Essentially this is the same principle as an electrocardiograph that a doctor performs when checking a person's state of well being.

Let us now consider the capability of recording each aircraft and its systems performance during each entire flight and retaining this information on a magnetic tape. By the use of high speed ground playback and computer processing we will have the ability to recognize out of limit conditions and establish trend information which will enable the prediction of impending out of limit conditions. From this we expect to schedule unit removals at a convenient time ahead of a malfunction. This will permit us to take advantage of the system's potential reliability — extending utilization and thereby reducing overall operating cost and at the same time reducing further the percentage of flight delays.

Thought has also been given to the sudden or abrupt type failure. As we know from experience a unit may operate satisfactorily within limits for months and yet suddenly fail. We believe that previous to the malfunction there may have been slight indications which are warnings of impending malfunctions. We intend using the recording system as a tool to determine if there are significant warnings in advance of an actual failure.

Others in industry, like ourselves, are reaching for the benefits of the "on-condition" maintenance philosophy in lieu of time removals by statistical control. Through the use of recording programs similar in nature to ours data is gathered and trend and performance charts are plotted for analysis. This is particularly evident in the field of aircraft jet engines through log analysis studies. The readings and recording of data has been manual in nature for the most part, however it is significant that recording is being conducted.

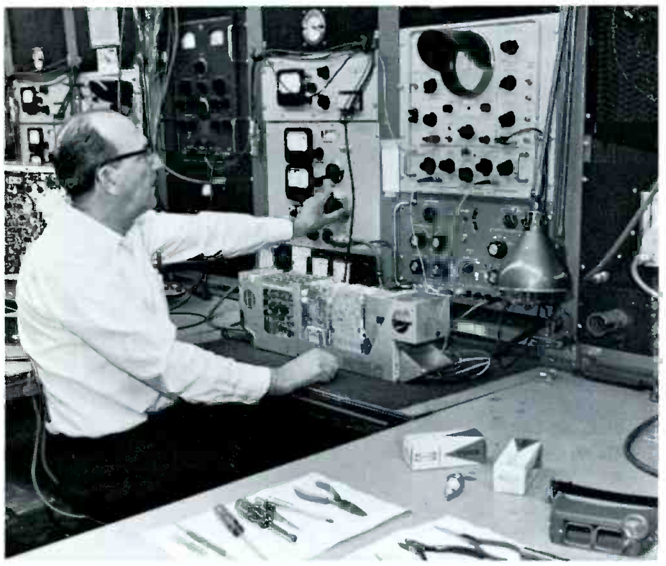


Figure 9 — When electronic units such as this DME Interrogator are removed from an aircraft, they are sent to the Kansas City Overhaul Base Shops where a large force of approximately seventy-five men keep TWA's electronic equipment in peak condition. The superior stability and long life of Machlett 7815 planar triode tubes used in the transmitter section help maintain optimum performance over long periods of time in service.

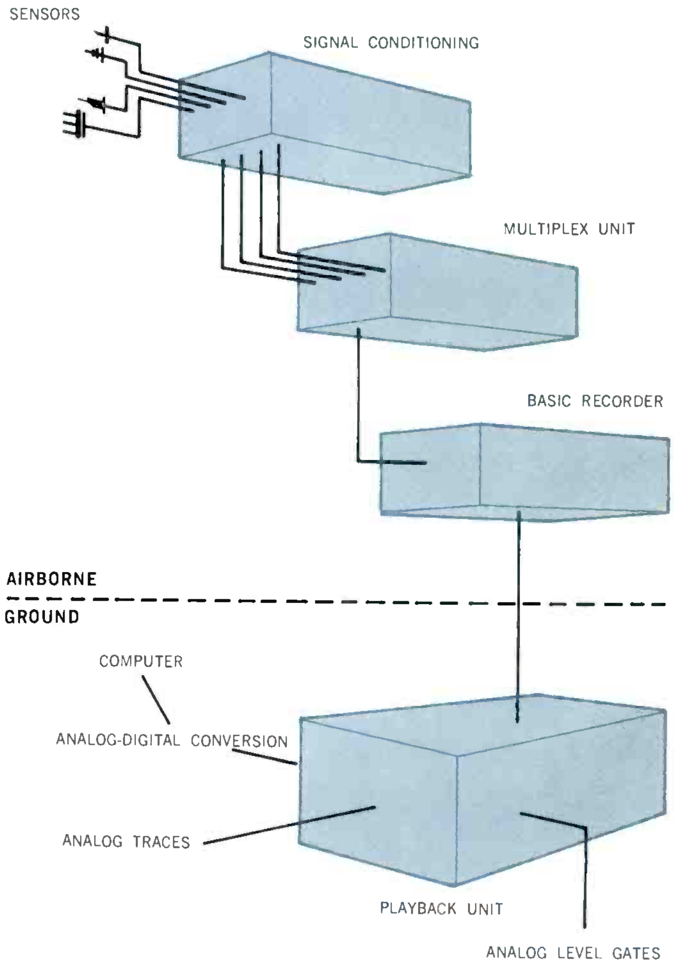


Figure 10 — The Airborne Performance Recorder monitors up to 315 individual parameters which can be analyzed and compared at high speed in the Ground Playback Unit and Computers. Much as an electrocardiograph is used to check a person's state of well being the Performance Recorder continuously checks the condition of an airplane. This analysis of recorded data makes it possible to predict impending out of limit conditions and schedule unit removals at a convenient time ahead of malfunction.

Our automatic recording program provides the advantages of:

1. Automatic recording
2. Higher sampling rate
3. More parameters
4. Increased accuracy
5. Faster processing for analysis
6. Correlation and computation of related parameters
7. Library of data for evaluation of aircraft and systems performance

Through these advantages we anticipate that we will not only be able to detect impending malfunction but will be able to run an audit and analysis of the fleets on a full time, 100%, aircraft basis. This, when applied to fleets of aircraft, would also enable the pinpointing of individually "sick" aircraft which may be responsible for fleets being off performance average. To our knowledge a continuous 100% fleet audit of individual aircraft performance has not previously been accomplished. Through the use of an airborne recorder we will be able to handle the performance analysis of individual aircraft on a daily basis and fleet on a bi-weekly schedule. This type of audit increases the sensitivity from which early signs of gradual performance deterioration can be detected and corrected. The result is expected to be a substantial monetary savings.

For example in 1962 TWA's fuel bill was over fifty million dollars. With only a two per cent improvement in our actual versus chart performance operation of our jet aircraft we can obtain savings in the order of one million dollars. We believe that such a saving is both realistic and obtainable."

It is not, we suspect, too large a flight of fancy to conceive of a time when, coupled with a telemetry system, and a suitable computer network that some SST* of the future may be maintained in flight and, to a large degree, automatically by virtue of the output of its own multiparameter performance recorder. Surely reliability must keep pace with performance — for, utltimately, there cannot be one without the other.

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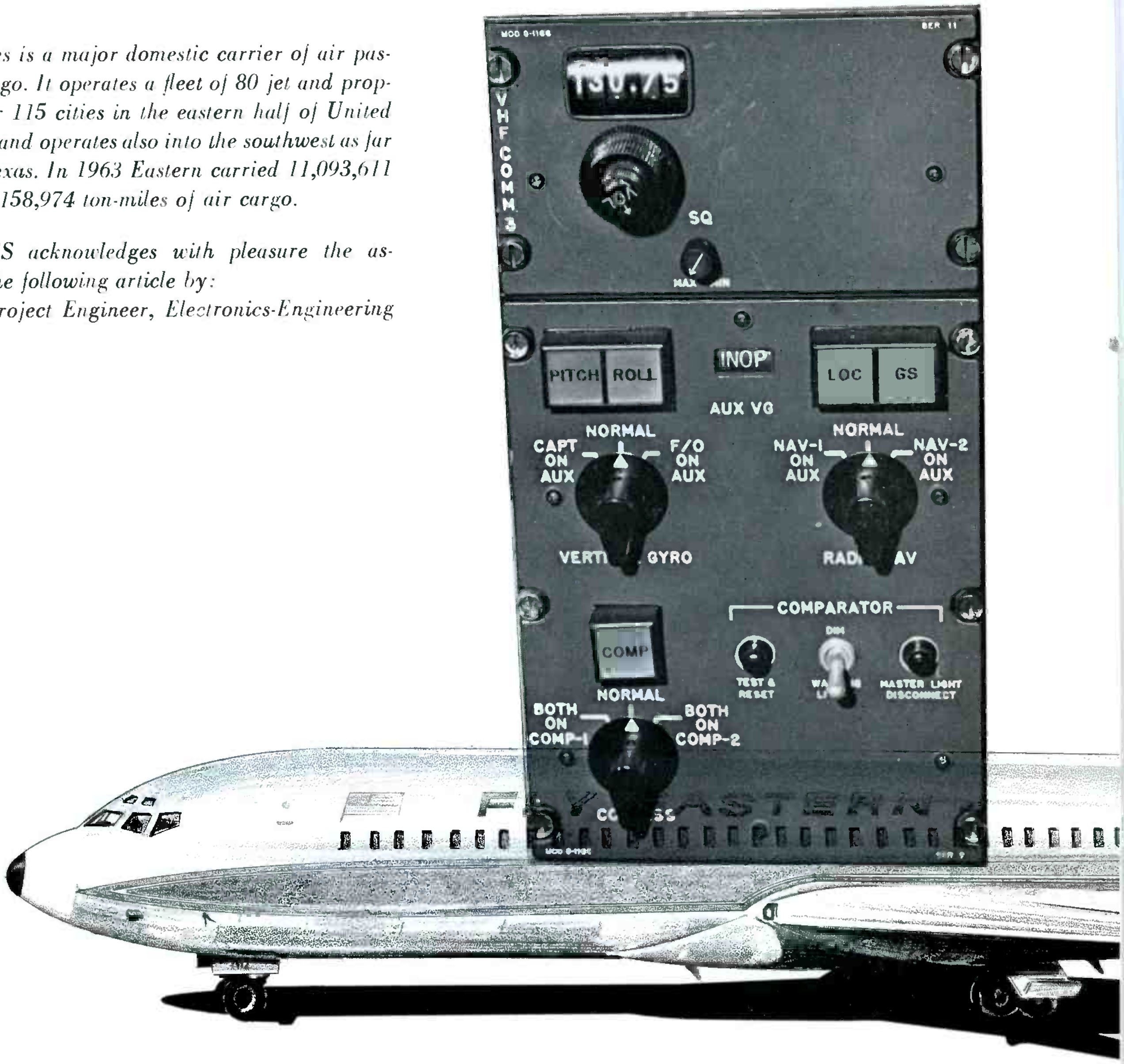
*Super Sonic Transport, operating at Mach 2 or Mach 3.

Editor's Note:

Eastern Air Lines is a major domestic carrier of air passengers and air cargo. It operates a fleet of 80 jet and prop-jet aircraft, to over 115 cities in the eastern half of United States and Canada and operates also into the southwest as far as San Antonio, Texas. In 1963 Eastern carried 11,093,611 passengers and 71,158,974 ton-miles of air cargo.

CATHODE PRESS acknowledges with pleasure the assistance given in the following article by:
H. F. Harrison, Project Engineer, Electronics-Engineering



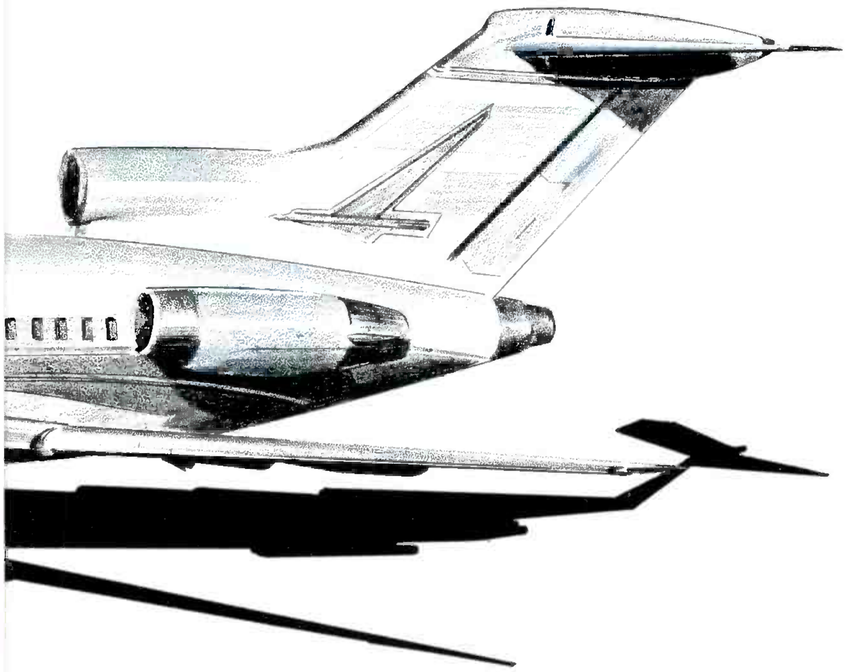
The Boeing 727, a 3 engine medium range jet, has been received with enthusiasm by the air transport industry. Nearly all carriers have plans to use the aircraft. Eastern Air Lines is one of an advanced group already using it. Although the EAL 727 has been in service for less than a year, plans concerning it — especially those relating to its electronics systems — have been undergoing development and definition since the plane was first conceived in 1959.

The primary interest behind these electronics plans was the ultimate desire to eliminate "the practice of scheduled removals" while, at the same time, operating the equipment "on a continuous service basis." As new as the aircraft itself, these plans — named Controlled Maintenance — proposed to 1) utilize the most reliable and advanced electronic equipment (so as to eliminate random failure problems); and 2) as far as possible, to make the aircraft its own test bench (by including self-test provisions for all major devices utilized by the B-727). To this end a set of general specifications were prepared.

General Specifications for Controlled Maintenance

1. Use of solid state devices:
   a) in place of vacuum tubes, where feasible. (In this connection the Machlett planar triode has found itself as much a part of the old order as the new.

Eastern Air Lines — Controlled Maintenance: A New Concept.



Machlett planar triodes have served as the most highly stressed device — the transmitting element — in some of the nation's most important space vehicles; Mercury, Mariner II, as well as others. In this respect, equipment design aboard Eastern's 727 is one with the space craft.)

b) in place of mechanical relays (with some exceptions).

c) for frequency selector switching.

2. Elimination of rotating electro-mechanical devices (e.g., dynamotors). Solid state switching is used to develop high voltage when needed.
3. Elimination of heat producing devices to achieve low ambient operating temperatures.
4. Use of self-test circuitry so that the line mechanic may confirm correctness of equipment operation.
5. Optimization of ramp tests of inter-related devices and provision of test points for this.
6. Improvement of controls and warning devices for the flight crew with considerations for improvement of devices which will permit more accurate analysis of equipment performance.

As a result of these design concepts Eastern has been able to introduce its new service concept.

"The Eastern B-727 electronics installation will incorporate self-test features which will enable the line mechanic to periodically confirm correct performance without the

Figure 1 — EAL's new B-727 at the Miami overhaul base is checked-out and readied for the next flight.

necessity of removing the equipment from the airplane. Eastern intends to schedule such periodic sampling at reasonable periods to assure correct performance tolerances. This procedure will be identified as a Controlled Maintenance program to differentiate from the old maintenance concept."

Included in this program, of course, are the DME and Transponder equipments.

Equipment Redundancy

Although equipment redundancy is associated with most commercial aircraft, the integration of redundancy with Controlled Maintenance on the B-727 provides an important new departure.

Equipment redundancy on the most used aircraft systems is normally limited to duplication. Here, for the first time, triplication is used (VOR, ILS, Vertical Gyro, VHF Communications), with the third unit being, in each case, carried as a "hot spare". Each equipment serves not only as back-up for in-flight use, but provides an extended reference base for "self-test" and comparator monitoring of equipment on the aircraft. Further to this, a continuing goal of the Controlled Maintenance program will be the development of new schedules within which equipment removal will be unnecessary.

System Comparison

An Instrumentation Comparator system is utilized to monitor dual systems in the aircraft. If a disparity develops the pilot is alerted by a Master Comparator Warning Light plus a sub-system light which indicates the system in which the disparity exists. With the ability to select a third system, the malfunctioning equipment may be "ferreted out" and disconnected from the system.

The following are compared and the pilot is warned when the indicated tolerance between the dual systems is exceeded:

Roll	4 degrees
Pitch	4 degrees
Heading	6 degrees
Localizer	30 microamps
Glide Slope	50 microamps.

Controlled Maintenance Checks

A "Bench Service Interval" has been established for certain B-727 electronics equipment, including the DME (Interrogator) and Transponder (Control Panel) whereas the DME Indicator and Antenna and the Transponder itself are maintained on an "On Condition" basis. These represent an important departure from the "Hours Scheduled" basis. An equipment will be maintained on board the aircraft by "Periodic Checks" and "Inspections" (as described by EAL Specifications). When indicated by either failure or other indication "On Conditions" equipment is removed for a "Bench Service" performed in accordance with established Shop Test Procedures. In this manner, Eastern plans to avoid needless removal of equipments and permit them, so to speak, to establish their own removal rates.

The units listed below are maintained on the Code I program procedure (the Phase Check Code I of the Periodic Service Period has been designated as the ultimate acceptable time interval for a thorough Operational Check of the Electronic Systems and Equipment).

A. VHF Communications System (VHF-1, VHF-2 & VHF-3).
B. Interphone Systems (Flight & Service).
C. Passenger Address System.
D. Radio Navigation Systems, Localizer, VOR & Glide Slope (NAV-1 & NAV-2).
E. Compass Systems (No. 1 & No. 2 Remote and Magnetic).
F. Integrated Flight Systems (Capt. & Pilot).
G. Instrumentation Comparator System.
H. Automatic Direction Finder System (ADF-1 & ADF-2).
I. Marker Beacon System.
J. Distance Measuring Equipment Systems (DME-1 & DME-2).
K. ATC Transponder Systems (TRANSP-1, NORM & TRANSP-2, AUX).
L. Radar System.
M. Automatic Flight Control Systems.

Self-Test: DME & Transponder

DME Self-Test

Self-Test for the DME begins with equipment in operation, flag up (blocking view of mileage reading on indi-

Figure 2 — Eastern Airlines' B-727 cockpit showing new instrument comparator system.

Figure 2A — Basic to the Controlled Maintenance plan is the instrument comparator which integrates instrument readings and provides a continuous comparison between the dual systems in use.

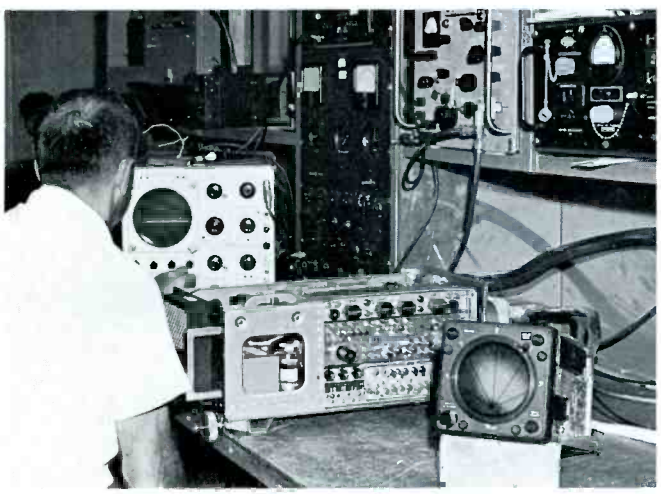


Figure 3 — Test Bench for Transponder Overhaul. Shown is the Wilcox 714B transponder. Use of Machlett tubes (ML-6442) in this equipment has significantly reduced replacement rate.

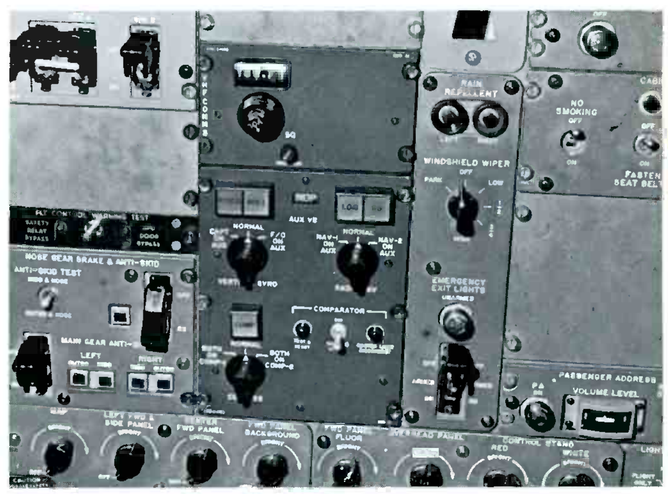


Figure 4 — View of Electronics Overhaul section for maintenance of radio-navigation equipment. Work is done here on these units: Radar, DME, Transponder, Glide Slope Equipment, Omnidirectional Receiver, Course Indicator, LORAN and also the Engine Analyzer. Other sections maintain Communications gear and instruments.

cator), with system in search mode. When the Self-Test Switch is pressed; the flag should retract, the counter rotate to zero ± 0.2 mi., and the DME should lock on. Upon release of the Self-Test Switch the DME should resume the search mode. A return of the DME/STBY switch to Standby should cause the flag to show and stop rotation of the mileage indicator.

The Self-Test checks the decoder, instrumentation and all circuits not normally checked by the flag circuits. The test is used in conjunction with local DME stations or standard ramp test equipment.

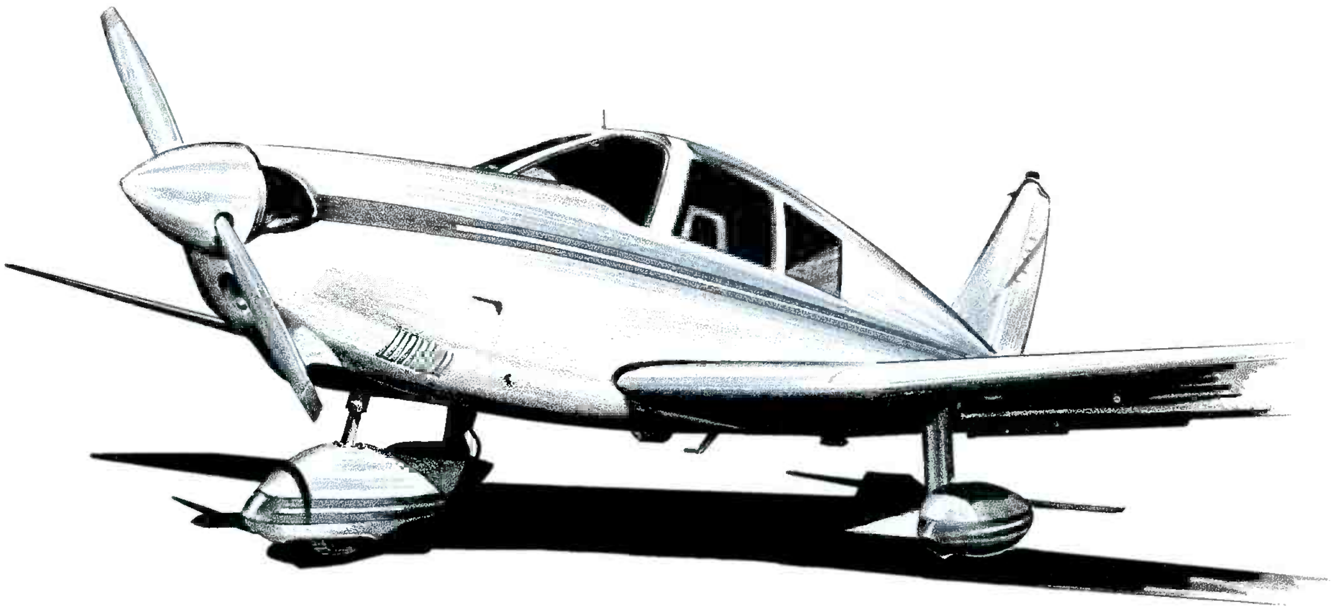
Transponder Self-Test

Self-Test for the Transponder utilizes positive test light indication to check the receiver, transmitter and framing pulses. This test is also augmented by standard ramp test equipment to check the accuracy of the coding.

Self-Test is also provided for: VOR, localizer and glide slope; marker; VHF Communications, radar and automatic flight control systems.

A Wide Range of Utilization is Met by a New Microwave Energy Source

By Ralph Barkes, Trak Microwave Corporation
As told to CATHODE PRESS



Introduction

A transmitter oscillator for transponders built to meet the ARINC No. 532D specification has been developed by Trak Microwave Corporation. This uhf oscillator satisfies the critical requirements for frequency stability as a function of environment and system operating variables. The oscillator provides maximum performance with the ML-8403 frequency-stable, large cathode uhf planar triode but will operate within less critical parameters with the use of other planar triodes.

General

The minimum performance specifications for ATC Transponder Equipment for use in ATC Radar Beacons have, since their publication in 1960, served as a goal as much as a guide. While anticipating the need for increased transponder utilization — yet at the same time recognizing the practicalities of the design process — these specifications have established a system whose ultimate performance is yet to be realized. With the maximum development of this system the Transponder will include not only the present IFF function (which includes climb and descent coding) but will include altitude reporting and either "discrete airframe identity" or flight identity. As in the case of any airborne equipment, complexity and performance must be subordinate to reliability and unit weight. For these latter reasons, among others, systems development has awaited a suitable device which could satisfactorily support all design parameters as envisaged by the 1960 specifications. The Trak 9506-1000 transmitter oscillator provides the basic microwave energy source for such a unit and does so because it takes full advantage of the frequency stable functions and high current provided by the Machlett ML-8403 planar triode.

Performance Specifications

Prior to describing this unit, a review of the specifications is in order.

Those factors primarily effecting the microwave oscillator itself involve: operating frequency and stability, reply code capability, transmitter power output and, to some extent, the reply transmission pulse characteristics.

Operating Frequency:

Typical Performance (Commercial)

1090 mc ± 2.5 mc

Typical Performance (Private and General Aviation)

1090 mc ± 3.0 mc

Frequency Stability:

Maximum (Commercial)

The maximum allowable frequency drift under all service conditions is ± 2.5 mc.

Minimum (Commercial)

State of art establishes minimum.

Maximum (General Aviation and Private)

The maximum allowable frequency drift is ± 3.0 mc under service conditions of 1.5; 1.0 VSWR, any phase or reply rate variation.

Transmitter Power Output:

Commercial		Nominal 500 watts (27 db ± 3 db above 1 watt into 50 ohms)
Private & General Aviation	Above 15,000 feet	+24 to +30 db above 1 watt*
	Below 15,000 feet	+20 to +28.5 db above 1 watt*

Reply Pulse Shape:

Commercial:

Rise Time: 0.1 usec or less

Duration: 0.45 ± 0.1 us at 50% point

Decay Time: 0.2 usec or less

Pulse amplitude variation in constituent pulses is less than ± 5%

Private and General Aviation:

Rise Time, Duration & Decay Time same as above.

Pulse amplitude variation in train, 1 db relative to any other pulse.

Reply Rate:

Commercial: 2000 groups/sec of 4 pulse reply

4000 groups/sec of 2 pulse reply

Private and General Aviation:

1200 groups/sec of 4 pulse reply-over 15,000 feet

1000 groups/sec of 2 pulse reply-under 15,000 feet

*This assumes that the antenna and transmission line losses are 3 db.

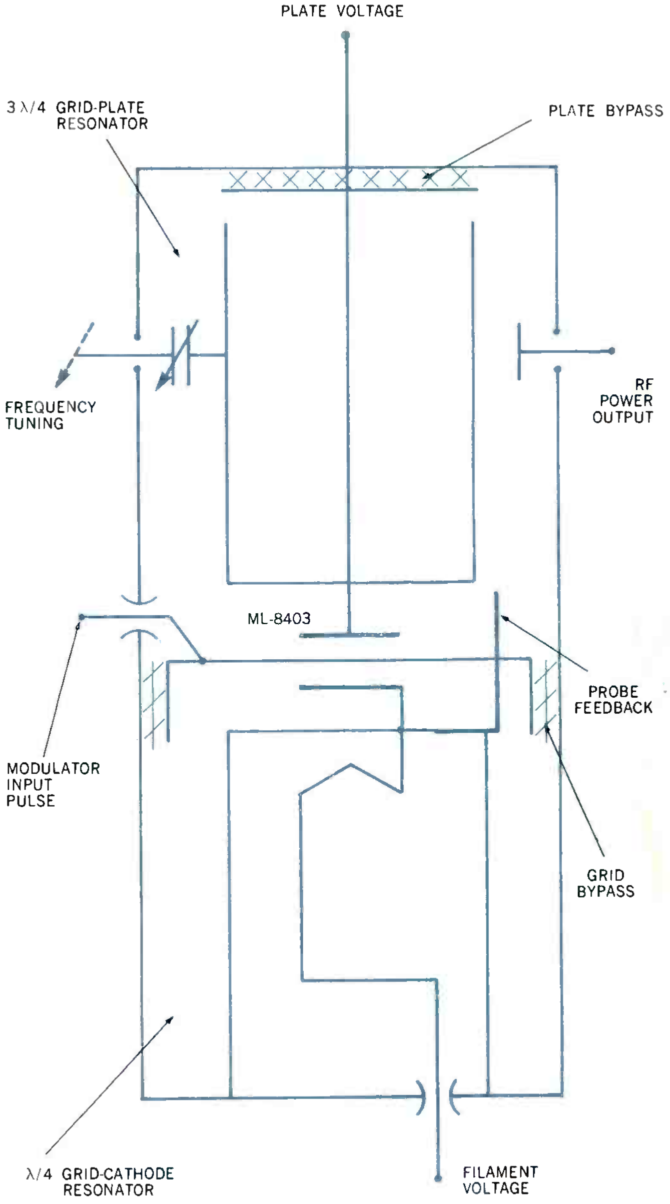


Figure 1 — Transmitter Oscillator Equivalent Circuit.

Design Considerations

General

Almost immediately after having discovered that the designer has a device that will work, he is confronted with the question, How much "work" should be built in and for what cost? The economics of design, in short, achieve a commanding position very nearly from the start. In terms of the Trak 9506-1000 the position was taken that (given a specific unit size, not requiring pressurization) this one unit would meet all ARINC 532D specifications, and by the substitution of different tube types, would meet all needs up to this established maximum. Table 1, below, lists these variations.

TABLE 1

Typical Application	Tube Type	General Operating conditions
Low performance aircraft	ML-7289/ 3CX100A5 or ML-7815	Low duty cycle Variable duty cycle stability not critical Some frequency deviation with loading allowable
Basic unit for low performance aircraft, but operating in crowded area	ML-7855	Low duty cycle Frequency deviation with loading must be tightly controlled
Low performance aircraft operating in uncrowded areas with large distances between landing fields	ML-7698	High duty cycle; high power Some frequency deviation allowable
Hig` performance commercial, executive, ilitary aft	ML-8403	High duty cycle; high power Frequency deviation with loading must be tightly controlled

, build one oscillator — or microwave energy source — ’ould span this range required considerable skill in the ba ice of the conflicting parameters of cost and capability.

In general terms these were resolved by the choice of:

1. Unit size. A size was chosen such that pressurization was not needed, but which could still provide altitude capability to 55,000′. Size reduction beyond that of the 9506-1000 would have necessitated pressurization to avoid arcing or corona effects.

2. Frequency deviation vs. power output limits. To compensate for antenna loading, effects of cable length on loading and yet maintain a nominal power output together with a suitable frequency deviation vs. phase shift, the oscillator is designed to operate slightly de-coupled from the load; and feedback design is such as to enhance frequency stability. This means, of course, that for any given installation power may be increased (at the expense of frequency deviation, resulting from VSWR changes) by increasing the coupling or, in the case of undesirable loading effects, the frequency deviation may be improved, somewhat, at the expense of lowered power.

It is important to note, however, that the choice of parameters is such that for most general or commercial installations load isolation is not required. This in itself, effects a cost saving of considerable magnitude.

3. Use of the planar triode. Competitive with other

Figure 2 — Power Versus Plate Voltage

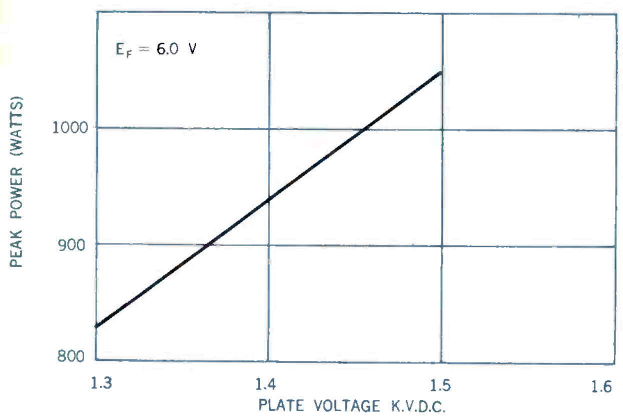


Figure 3 — Frequency Deviation Versus Plate Voltage

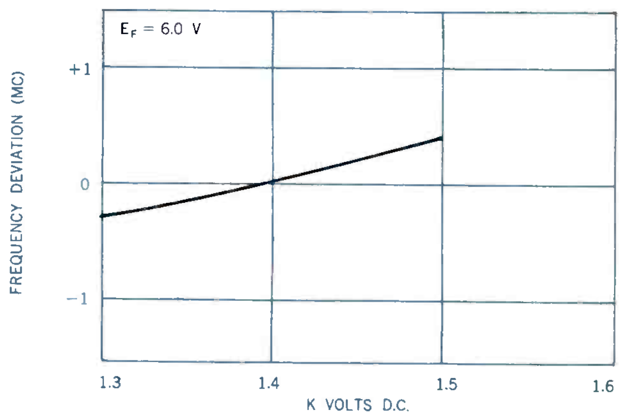


Figure 4 — Frequency Deviation Versus Phase Shift

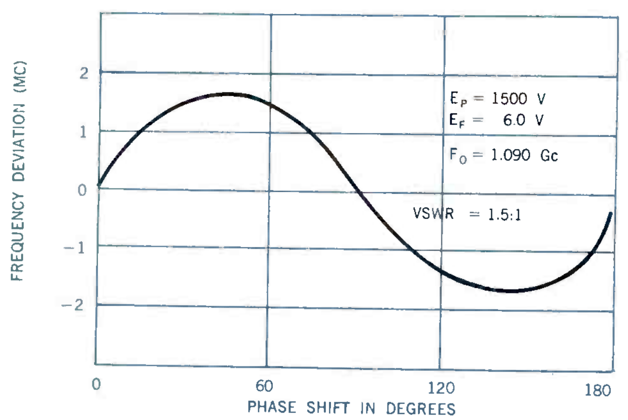
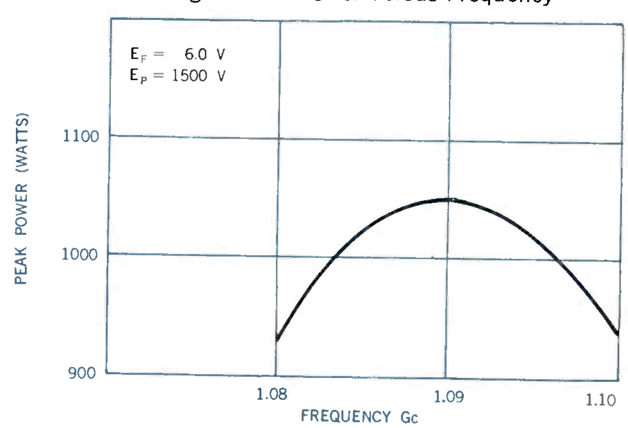


Figure 5 — Power Versus Frequency



devices, such as the klystron and magnetron, the planar triode in this installation offers advantages of considerable magnitude in relation to cost (low, replaceability (simple), life (very good), and reliability (very good); electrical requirements (e.g. drive), plate voltage easily realized); performance (good to outstanding). It is in this latter category that the planar triode makes its mark — and the ML-8403 in particular. Perhaps more than any other factor this tube has allowed a significant simplification in oscillator design with its combined advantages of relatively high power and frequency stable performance.

Where the oscillator designer is forced to compensate for the thermal effects of a variable duty cycle by electrical or electronic means the addition, at the very least, of a new black box would be necessary. Since this tube automatically compensates for the effect on frequency of variable duty cycle the whole problem is disposed of at the start.

4. Grid pulsed circuitry. Grid pulsing of the planar triode permits further design simplification by reducing by a factor of 10 or more the pulsing power required. Here the phormat cathode of the ML-8403, ML-7698, ML-7815 or ML-7855 allows reliable performance. It is apparent that the low pulsing voltages associated with grid pulsing permit use of a considerably smaller and more economical power supply than would otherwise be the case.

TYPICAL SPECIFICATIONS

FREQUENCY: 1090 Mc ±10 Mc.

PART NUMBER: 9506-1000.

POWER OUTPUT: 500 watt minimum.

POWER INPUT REQUIREMENTS: 1500 VDC plate at 2.5 amp. peak plate current max., —50 VDC grid bias with +80 V peak grid pulse max., 6.0 VDC E_{fil} at 1.25 amp. nominal.

ALTITUDE: 55,000 ft.

TYPICAL FREQUENCY STABILITY CHARACTERISTICS ARE:

Frequency vs. E_{fil} ±0.20Mc for 6.0 V@±3% regulation.
Frequency vs. E_p ±0.40Mc for 1500 V@±5% regulation.
Frequency vs. VSWR ±1.50Mc for 1.5: 1 all phase angles.
Frequency vs. duty ±0.15Mc for .001 to .002 duty (.01 duty max.)
Frequency vs. temp. ±0.25Mc for —10°C to +55°C (±0.50Mc for —54°C to +90°C.)

Total frequency stability characteristics are ±2.50Mc max.

Physical: 2 in. diameter by 5 5/16 in. long excluding projections.

Weight: 13 ounces in aluminum, 30 ounces in brass.

As a triode oscillator, advantages over other types include smaller size and lighter weight, plus operating economy. The replaceable triode means that the oscillator, at end of tube life can be brought back to optimum performance at nominal cost by replacement of the triode.

Design considerations — Detail

Suitable structural design required a light metal, easily machinable and with good thermal or heat absorption characteristics. Aluminum was selected as the most desirable metal even though its coefficient of expansion is greater than that of Kovar or invar. However, techniques associated with Trak's manufacturing processes — plus use of the ML-8403 — preclude the possibility of frequency instability.

To further enhance stability the use of a ¾ λ grid-plate resonant line was chosen. This choice was indicated by the greater frequency stability vs. VSWR changes throughout all phase angles. The improvement in VSWR pulling stability being achieved by creating a resonant circuit with greater stored energy. This ¾ λ section was folded back as shown in Figure 1 so as to provide compactness in size.

Once these basic, but highly important, decisions were made, the design dimensions were determined by certain prescribed formulas while taking into consideration that physically long arc paths were required in an unpressurized unit to prevent corona or arcing at high altitude operation.

In brief form, the basic formulas required to determine the final mechanical dimensions are shown below:

$$(1)\quad \lambda/4\ (\text{air}) \simeq \frac{3000}{f_0(\text{mc})} = 90^\circ$$

$$(2)\quad X_C = \frac{.159}{f_0 C}$$

$$(3)\quad \text{At resonance } X_C = X_L = j\, Z_o \tan \Theta$$

$$(4)\quad Z_o = 138 \log D/d \ (\text{for air dielectric})$$

WHERE

(A) F_0 = desired resonant frequency
(B) C = capacitance (hot) grid to plate or grid to cathode
(C) Zo = characteristic impedance of the resonant lines
(D) Θ = electrical links (degrees) of the transmission line circuit element.
(E) X_L = input inductive reactance of the transmission line which resonates with the given Xc
(F) D/d = ratio of diameters (outer/inner) of conductors of the resonant line.

Conclusion

As demonstrated in the typical performance specifications shown, the Trak 9506-1000 microwave energy source — using the Machlett ML-8403 planar triode — achieves the design objectives provided by, and allows full compliance with, the ARINC specification 532-D.

New Machlett Developments

Tetrodes for Broadcast/Communications Applications

ML-8170/4CX5000A

ML-8281/4CX15000A

The ML-8170/4CX5000A and ML-8281/4CX15000A are general-purpose, high frequency, forced-air-cooled tetrodes designed to provide stable, long-life oscillator, amplifier, or modulator service. The internal structure of these tetrodes is so designed as to permit high rf operating efficiency with low rf losses, at frequencies to 110 Mc. Envelopes are of sturdy, low-loss coaxial ceramic-to-metal construction.

MAXIMUM RATINGS AND TYPICAL OPERATION

RF Power Amplifier & Oscillator — **Class C Telegraphy (key down conditions)**

	ML-8170/ 4CX5000A	ML-8281/ 4CX15000A	
Maximum Ratings, Absolute Values			
DC Plate Voltage	7.5	10	kV
DC Screen-Grid Voltage	1500	2000	V
DC Plate Current	3	5	A
Control-Grid Dissipation	75	200	W
Screen-Grid Dissipation	250	450	W
Plate Dissipation	5	15	kW
Typical Operation			
DC Plate Voltage	7.5	10	kV
DC Control-Grid Voltage	—350	—550	V
DC Screen-Grid Voltage	500	750	V
Peak RF Grid Voltage	590	790	v
DC Plate Current	2.8	4.6	A
DC Control-Grid Current	.25	.28	A
DC Screen-Grid Current	.50	.55	A
Plate Dissipation	5	9	kW
Driving Power, approx.	150	220	W
Plate Power Output, approx.	16	36	kW

[WORLD'S HIGHEST POWER TETRODE]

The New Vapor-Cooled ML-8545

Another Machlett innovation. The ML-8545 is a general-purpose tetrode capable of 300 kW continuous output as a Class C amplifier or oscillator at frequencies to 50 Mc. Maximum plate input is 420 kW, and is substantially higher during momentary overloads or intermittent operation.

Applications include:

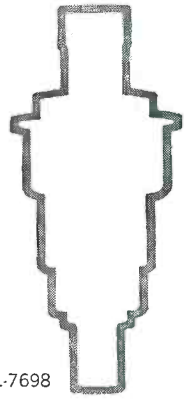
- High-power broadcast and communications
- All-purpose rf generation
- Particle acceleration

For further data on the ML-8545 and the ML-8546, water-cooled version, write: The Machlett Laboratories, Inc., Springdale, Conn. An affiliate of Raytheon Company.

MACHLETT

ELECTRON TUBE SPECIALIST

[MACHLETT UHF PLANAR TRIODES]



ML-7698

ML-8534
ML-8536

demonstrated reliability in Mariner II, Mercury and Ranger programs.

HERE'S WHY:

Phormat Cathode: High voltage stability for grid or plate pulsed applications. Phormat (matrix) cathodes have been tested to 12,000 volts and more. Used in planar triodes ML-7211, ML-7698, ML-7815, ML-8403, ML-8533 and all Miniature Planar Triodes.

Frequency Stable Anode: Unique anode design allows frequency stable operation within 10-15 seconds after application of high voltage, plus these advantages:

1. Frequency shift during initial tune-up less than 1 Mc.
2. Does not require regulated plate supply, since change of anode dissipation does not affect frequency.
3. Permits variable duty cycle without noticeable shift in frequency.

Used in planar triodes ML-7855, ML-8403, and Miniature Planar Triodes, ML-8534, ML-8535, ML-8536 and ML-8537.

High Cathode Current: 50% more cathode current (190 vs. 125ma) permits power to 110 watts CW. Used in planar triodes ML-7211, ML-8403 and Miniature Planar Triodes, ML-8534 and ML-8535.

Pulsed Operation: High voltage stability—phormat cathode provide reliable pulsed service (see table).

SPECIFICATIONS OF MACHLETT PULSED PLANAR TYPES

Miniature Tube Type	Conventional Tube Type	Plate Pulsed Max f	Plate Pulsed Max Power input	Grid Pulsed Max f	Grid Pulsed Max Power input
—	ML-6442	5Gc	3000 v eb 2.5 a ib	—	—
—	ML-6771	6Gc	2500 v eb 1.5 a ib	—	—
—	ML-7210[1]	3Gc	3500 v eb 2.8 a ib	—	—
ML-8535[2,3,4]	ML-7211[2]	3Gc	3500 v eb 5.0 a ib	3Gc	2500 Vdc Eb 5.0 a ib
ML-8534[2,3,4]	ML-7698[3]	3Gc	3500 v eb 5.0 a ib	3Gc	2500 Vdc Eb 5.0 a ib
ML-8536[3,4]	ML-7815[4]	3Gc	3500 v eb 3.0 a ib	3Gc	2500 Vdc Eb 3.0 a ib
ML-8537[3,4]	ML-7855[3,4]	3Gc	3500 v eb 3.0 a ib	3Gc	2500 Vdc Eb 3.0 a ib
ML-8535[2,3,4]	ML-8403[2,3,4]	3Gc	3500 v eb 5.0 a ib	3Gc	2500 Vdc Eb 5.0 a ib
ML-8538[3] ML-8539[3]	ML-8533[3]	DC Pulse Modulator DC Plate Volts 8 kv	Pulse Cathode Current 5.0 a ib	3Gc	8000 Vdc Eb 5.0 a ib

[1] 12 second warm-up. [2] High current cathode. [3] Phormat cathode. [4] Frequency stable anode.

Send for UHF Planar Triode Brochure for data, application notes, cavity information, installation notes—over 100 pages of information.

The Machlett Laboratories, Inc., Springdale, Connecticut, an affiliate of Raytheon Company.

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