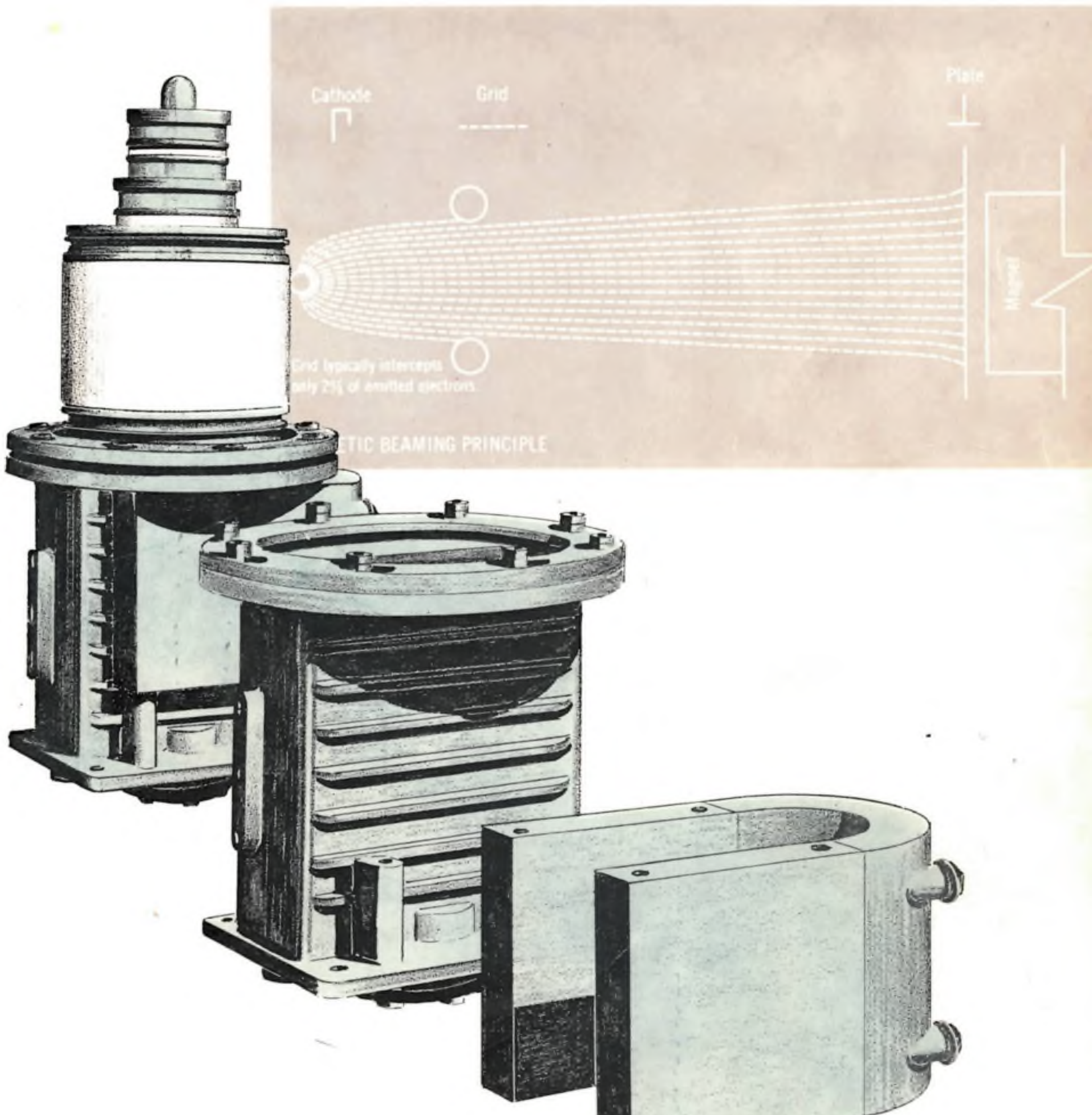
MACHLETT CATHODE PRESS



VOL. 22 • NO. 4 • 1965

Biographies

ERICH PETER

Erich Peter, who received his ME degree from the University of Bridgeport and who is currently engaged in studies for his MS at the University of Connecticut, has been a member of the Machlett engineering staff since 1959. Mr. Peter has been active in the design and development of high voltage, high power radar and transmitting tubes; tubes for operation in severe mechanical environments; on novel cooling systems and on the new magnetic beam triode line.

HELMUT LANGER

Helmut Langer, who received his EE degree from the Ingeneurschule Barth, Berlin, in 1949 and who attended the Technical University there, worked as an engineer for the Telefunken Company prior to coming to Machlett in 1954. Now a Senior Development Engineer, Mr. Langer has developed high voltage, high power radar and transmitting tubes, both oxide cathode and thoriated-tungsten cathode types. Other important work includes: vapor cooling systems, magnetic beam tubes, and tubes for severe mechanical environments. He holds electron tube patents both here and in Germany.

JOSEPH B. SAINTON

Joseph B. Sainton is a Senior Engineer for Continental Electronics, Dallas, Texas. He is currently assigned to the communication section and is doing development work in commercial broadcast transmitters. He has been with Continental for fourteen years. Recent assignments as Project Engineer include work on 50, 100 and 500 kW transmitters. Holder of several patents, Mr. Sainton has U.S. and foreign patents pending for the high efficiency screen modulated amplifier described in this issue of CATHODE PRESS.

PETER BLOODGOOD

Peter Bloodgood received his B.S. degree in Physics from Columbia University, while working in Columbia's E.K.A. Physics Laboratory. After serving as a Power Tube Applications Engineer for a leading electronics firm, he joined Machlett Laboratories in 1965, where he is presently at work in the field of large power tube testing.

BARRY SINGER

Barry Singer, who obtained his BS in applied mathematics from the University of Colorado and his MS in the same subject from New York University, has been with Machlett since 1960 as a Design Engineer. Among the many projects Mr. Singer has undertaken are theoretical design studies for magnetic beam power tubes; he has performed similar studies on UHF cavities for use by the Company in the design and testing of its planar triodes.

CATHODE PRESS

Vol. 22, No. 4, 1965

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

Editor, *Richard N. Rose*

Art Director, *Edward J. Bulger*

IN THIS ISSUE

Cover . . . Magnetic beaming in power tubes — a significant new Machlett design — has permitted the development of highly efficient electrode configurations which effectively reduce grid current, and hence grid heating, a serious limitation. The ML-8618, a magnetic beam tube, is shown with water jacket and magnet; the background cut shows, schematically, the new principle.

DECEMBER 1965

MACHLETT

ELECTRON TUBE SPECIALIST

PRINTED IN U.S.A.

Greenville, U. S. A., the World's Largest

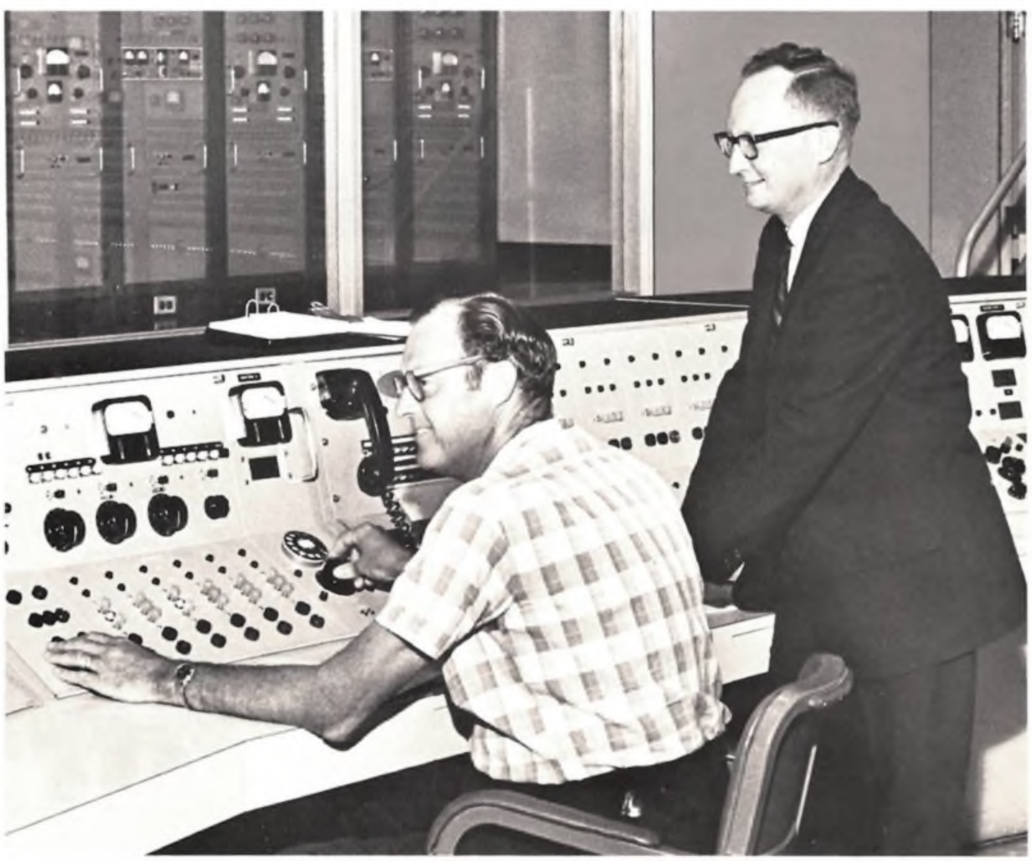
The ring of curtain antennas you see above covers a broad horizon — and yet, in length it is just under a quarter of the entire run of the great antenna field known, with magnificent understatement, simply as Site A. Site A of the Voice of America's Greenville Relay Station, like its near twin, Site B, radiates a total rf power of very nearly 3 megawatts — approximately that of all the 5 kW AM radio stations in the United States. . . . Sites A and B (and receiving Site C) cover some 6,100 acres and provide space for 95 antennas (curtain, log periodic, and rhombic), the two identical

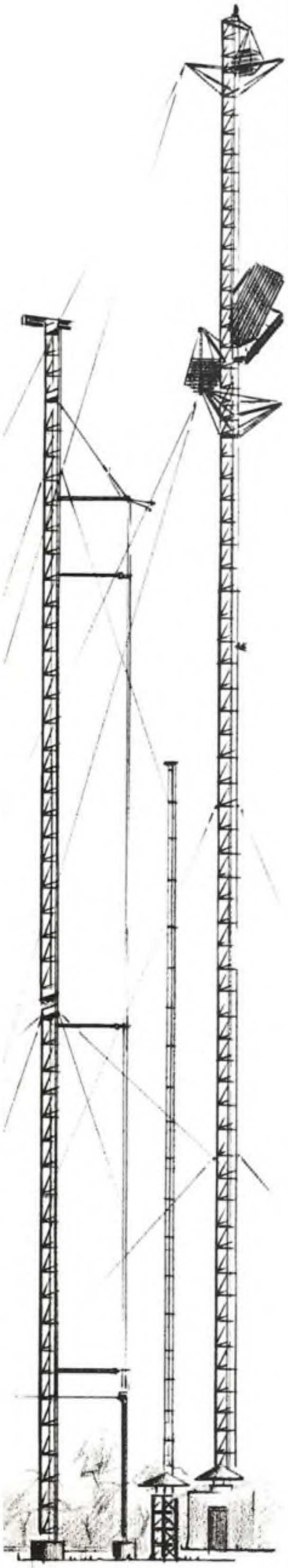
Broadcasting Facility 4.8 Mw

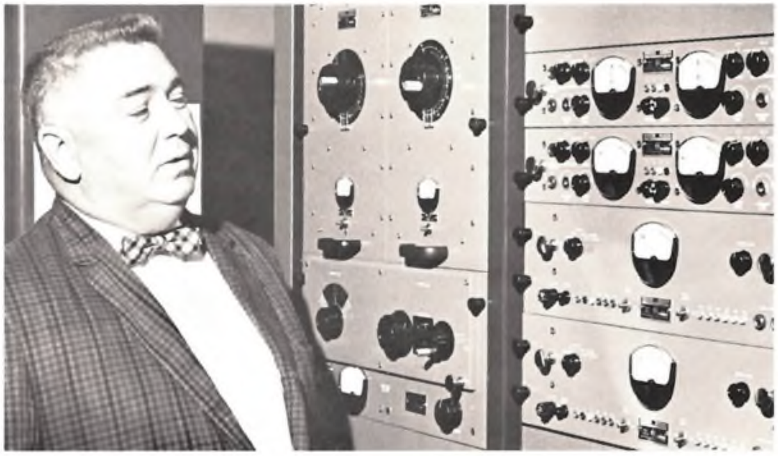
transmitter buildings and the administration/receiving building. This tremendous enterprise is now in its third year of twenty-four hour a day operation as the major link of the Voice between this country, Europe, South and Central America, eastern Russia and Africa. . . . The Greenville Relay station is very probably the largest broadcasting complex in the world. As such it attests to the importance placed by this country on the Voice of America, an importance well expressed by President Kennedy on the occasion of the twentieth anniversary of the Voice in 1962, when he said . . .

What we do here in this country, and what we are, what we want to be, represents a really great experiment in a most difficult kind of self-discipline, and that is the organization and maintenance and development of the progress of free government. And it is your task, as the executives and participants in the Voice of America, to tell that story around the world." . . . On a typical 24 hour broadcast day Greenville's transmitters will have broadcast over 160 programs in 32 languages — languages such as Urdu, Hindi, Russian, Tamil, Hungarian, Greek, Latvian, Polish and Portuguese. There are English broadcasts, too, of course, presenting among other matters: News, "Letters to the Editor," American short stories, folksongs, science in the news, jazz, and the American Musical Theater. There is also, for example, the Radio-English Teaching Branch whose long range program is to help people around the world improve their English, or to learn to speak it — and thus help establish a common language for all people. . . . Now that jamming has ceased the Greenville signal comes in loud and clear to the many millions within its listening area.

James Alley, Manager of the Greenville Station, shown here as he inspects operations at the master control panel, has lived with the Voice for twenty of its twenty-four years. He has been assigned posts with the VOA throughout its global network, most recently managing the large installation in Monrovia, Liberia, where he was stationed for two years. Nearly all of the supervisory staff at Greenville have had responsible positions in overseas locations — the Philippines, Okinawa, Greece, Liberia, West Germany, Morocco, Ceylon, and England. . . . There are, all told, nearly 100 employees under Mr. Alley's direction.







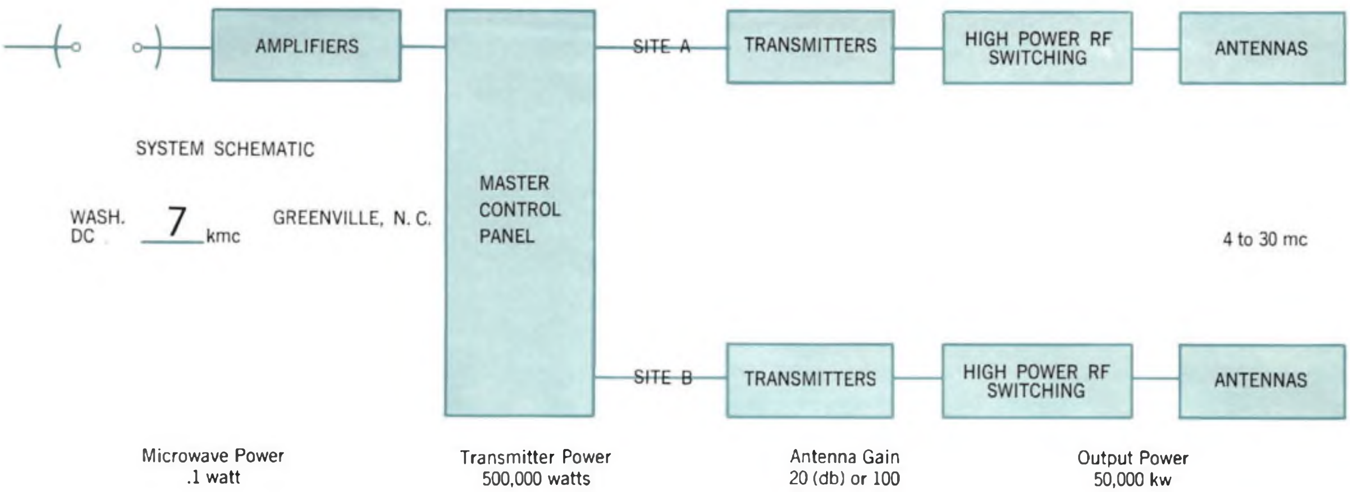
Deputy Manager William Slater — shown here inspecting the meter settings of a dual diversity receiver* — presides over the technical domain of the $23,000,000 Greenville facility, one whose electrical consumption is 60 million kwh annually. To be accounted for also are nearly 4000 electron tubes (plus, of course, the backup stocks) and hundreds of other items in regular use. . . . *The dual diversity reception system employs two antennas, spaced several wavelengths apart to feed two special receivers which are combined in such a way that the strongest signal is selected and amplified. In this way, the effects of short-term fading — resulting, for example, from ionospheric reflection — are practically eliminated. Multi-couplers are used to patch any receiver to any antenna.

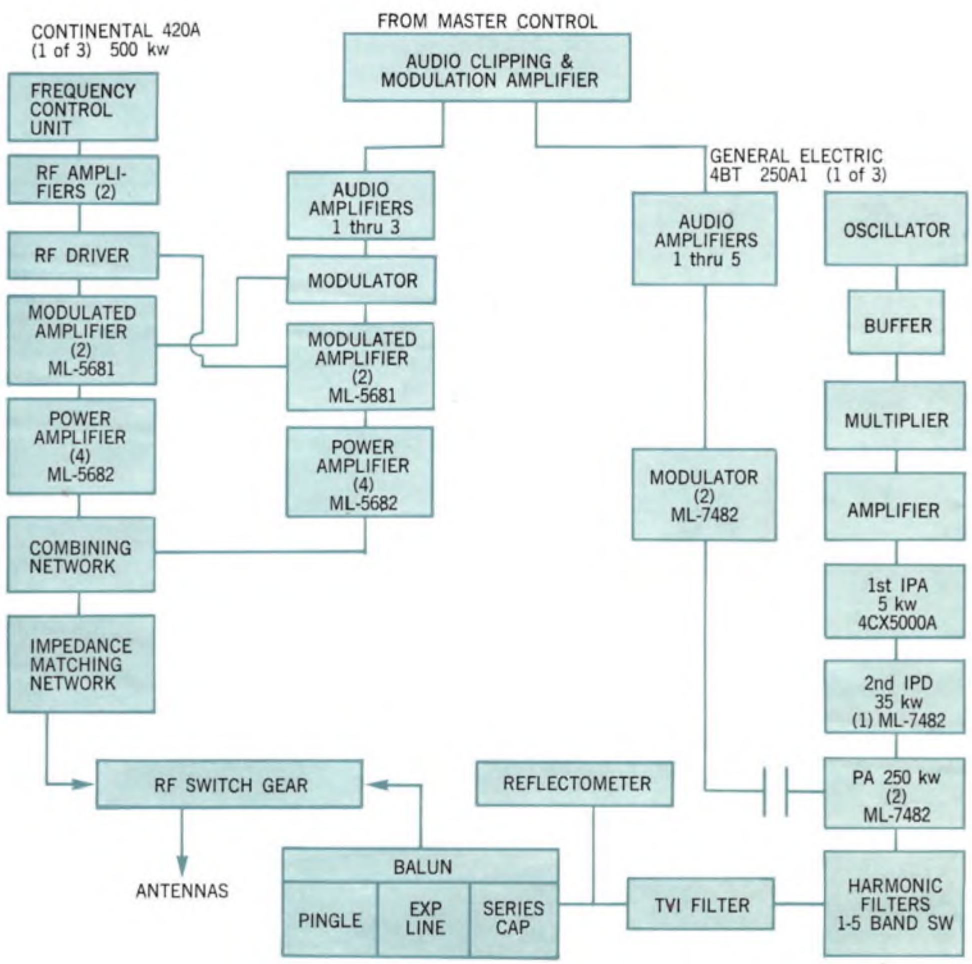
Beamed from Washington via a 7 Kmc microwave link and received at Site C is all the program information to be rebroadcast. A local microwave carries the Site C data to the transmitting sites. Backing up the microwave is a phone line, automatically switched in should a failure occur. Standby tapes are also held in reserve. . . . Twice daily the dual diversity receivers bring in material from Africa and elsewhere. This data is microwaved to Washington for inclusion in future programming, possibly the same day's . . . VOA teletypes, such as those shown here, carry over 100,000 words daily to support the 800 hours of VOA programming. (Taped programs and scripts are sent also to 5000 local stations throughout the world, for 13000 program hours. These additional programs are heard in as many as 65 languages by millions.)

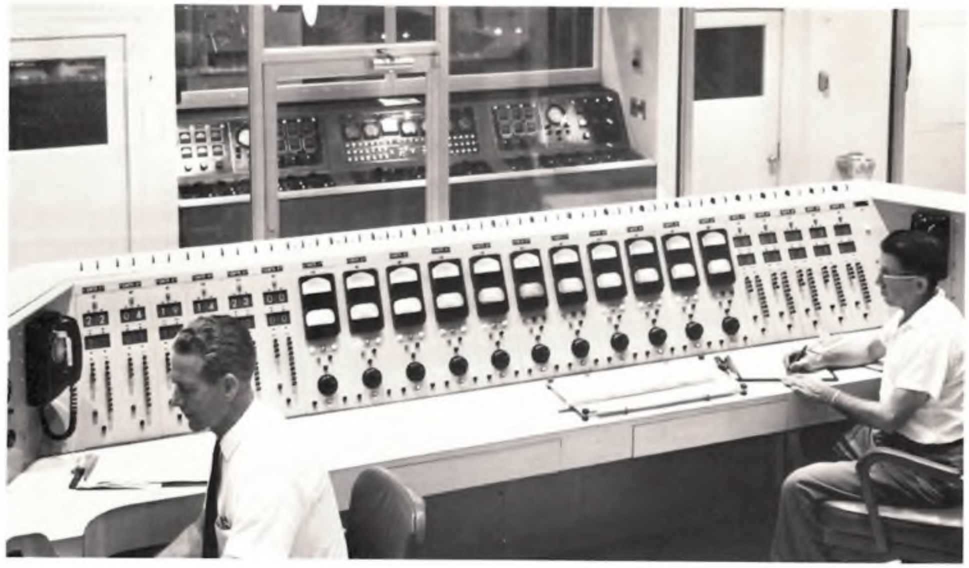
The transmitting sites are striking buildings — simple, handsome, surprisingly quiet. An initial glance might cause one to assume that operations had yet to begin, for there is no rush and bustle of people coming and going. But another glance provides another story: a total of no more than 3 operators, plus shift supervisor, control the output of the three 500 kW transmitters, three 250 kW transmitters, three 50 kW transmitters, and two 5 kW transmitters at each site. All units are not normally on simultaneously — but each must be kept ready for program assignment. The large transmitters beam program material direct to the listening audience, and provide communications backup for the United States Government should the need arise. The smaller transmitters provide SSB, point-to-point communications with the Liberia installation of the VOA.

A transmitter installation of this magnitude must be much more than a scale-up of a smaller unit. At the voltage-current levels employed, corona voltages are easily reached. Voltage gradients must always be kept in mind, from the beginning design to daily maintenance care. Exacting maintenance is essential at these powers since any failure can carry with it extensive and expensive damage. . . . Transmitter tuning (performed at "low power," i.e., 75 kW) is exacting at HF and efficient performance is essential in the megawatt power range. Monthly performance tests use both sine and square wave inputs, the first for response, and distortion, carrier shift and noise from 100 to 10,000 cps; the second for power at 9 frequency ranges from 100 to 3000 cps, within limits of ± .5 db. Daily tests are made on a simplified schedule.

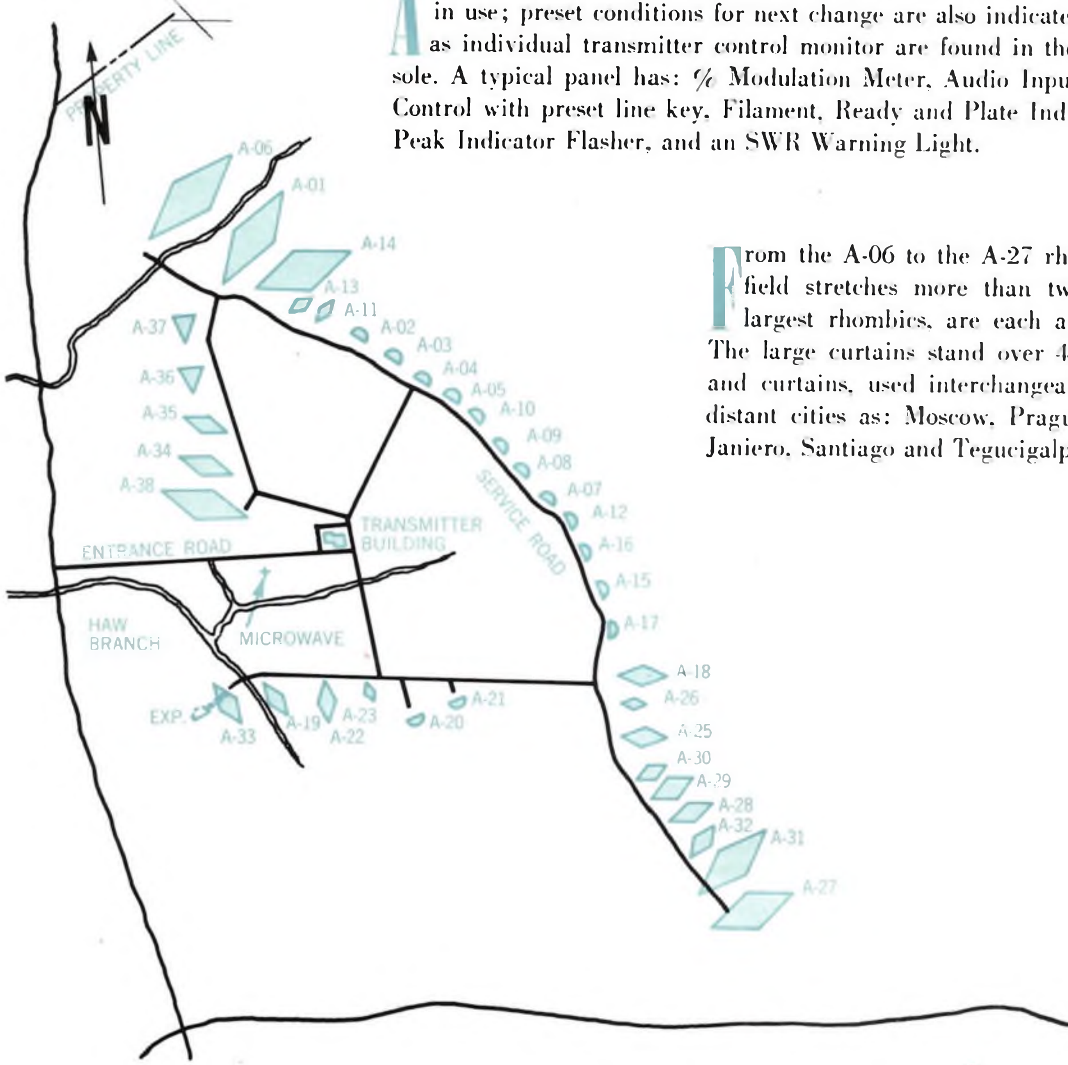
The two schematic diagrams below describe first, the overall system signal flow and second, the signal flow for the major transmitters. Total db gain for the system, from the incoming microwave to the output antenna is + 87 db. . . . The Master control panel, (a section of which is shown on page 8), located at Site C, despatches the many different incoming language programs to program control panels at Sites A and B.



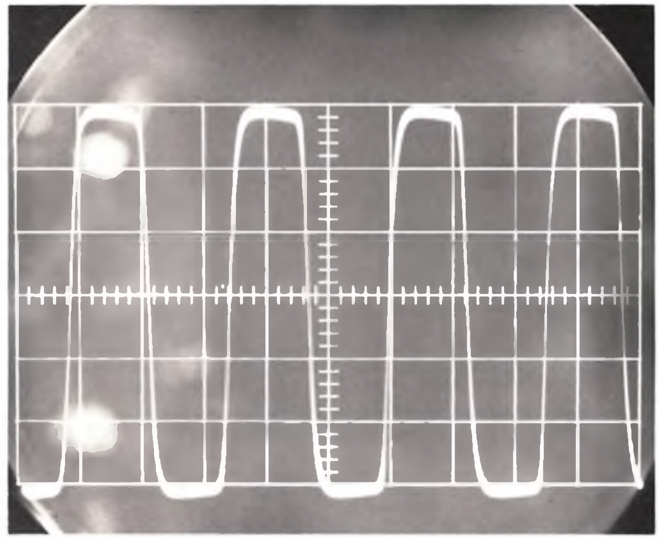




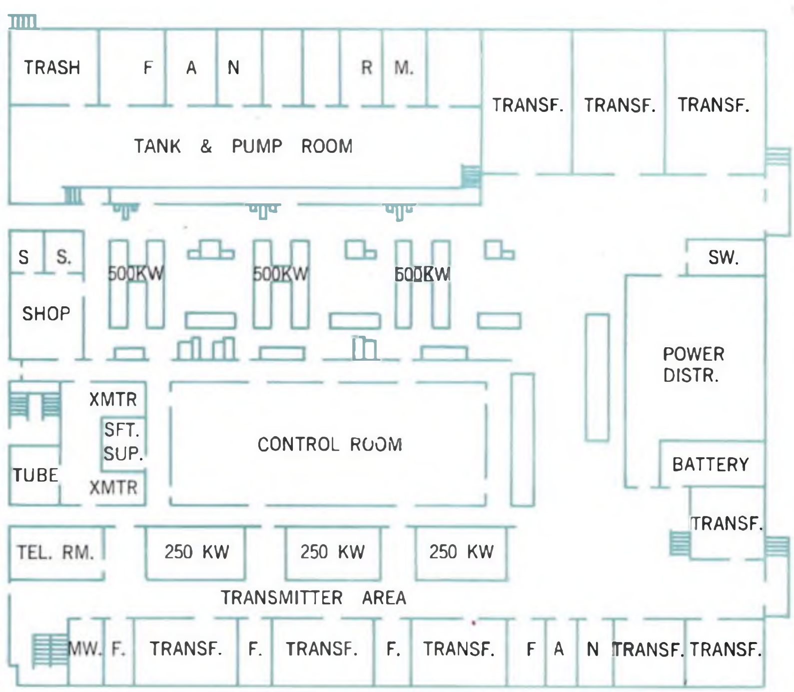
Antenna selection controls (to indicate the combinations of antennas and transmitters in use; preset conditions for next change are also indicated) and indicators as well as individual transmitter control monitor are found in the transmitter control console. A typical panel has: % Modulation Meter, Audio Input VU Meter, Audio Gain Control with preset line key, Filament, Ready and Plate Indicator Lights, Modulation Peak Indicator Flasher, and an SWR Warning Light.



From the A-06 to the A-27 rhombic antennas, this vast field stretches more than two miles. These two, the largest rhombics, are each approximately 1500′ long. The large curtains stand over 400′ high. Both rhombics and curtains, used interchangeably, are beamed at such distant cities as: Moscow, Prague, Cairo, Lagos, Rio de Janiero, Santiago and Tegucigalpa.

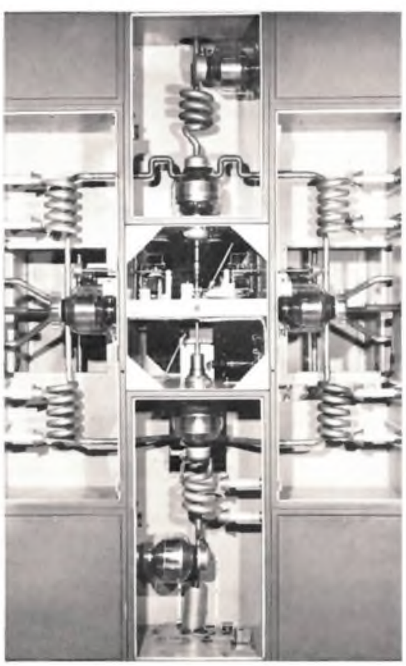


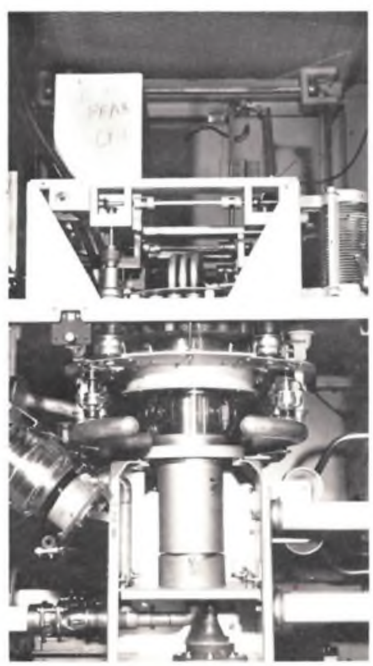
At the left is the control room of Site A. Nearly 70 feet in length, this huge room contains equipment for modulation monitoring, frequency control and antenna switching and the imposing control console. Above: the square wave form used for testing transmitter performance at high power levels. Normal operation employs 9 db of clipping: the transmitter is set up to clip speech at 6 db then the average level is raised by 3 db. Clipping is performed so as to enhance intelligibility (by high frequency pre-emphasis, and by low-or mid-frequency vowel clipping); over modulation is avoided by the clipping action. Below: A section, 160′ x 132′, of transmitter building.



Hose Company No. 1 put on this magnificent display for CATHODE PRESS. Fortunate, indeed, is a broadcast station to have such a convincing fire extinguisher. Three times blessed, the Greenville installation has three such units, one for each site. Designed for use in the antenna fields as well as at the buildings themselves, the fire trucks have, on occasion, been used to extinguish grass fires in antenna fields.

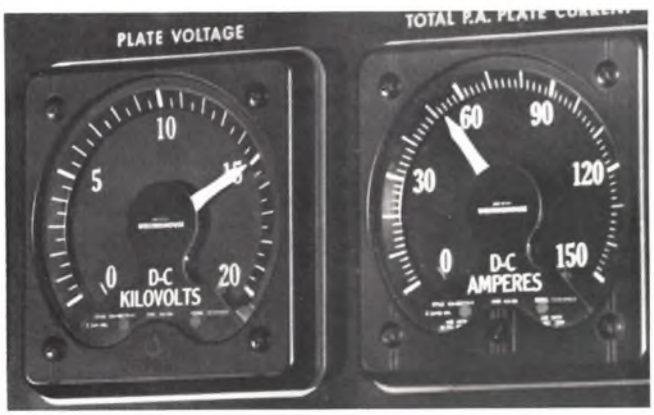
Below, left, the spacious bay which houses the three 500 kW transmitters. Visible, just below the ceiling of this room are the large protective ducts which house the high power rf lines. . . . The output combining network of the Doherty amplifier (essentially a double balanced rf bridge). This unit combines the output of the carrier and the peak power tubes. A following impedance matching unit connects directly to the rf transmission line. . . . An ML-5682 (one of four used) in the peak tube compartment. A modulated amplifier with ML-5681's drives the ML-5682's. . . . Vapor cooled ML-7482's in the modulator section of a 250 kW transmitter.





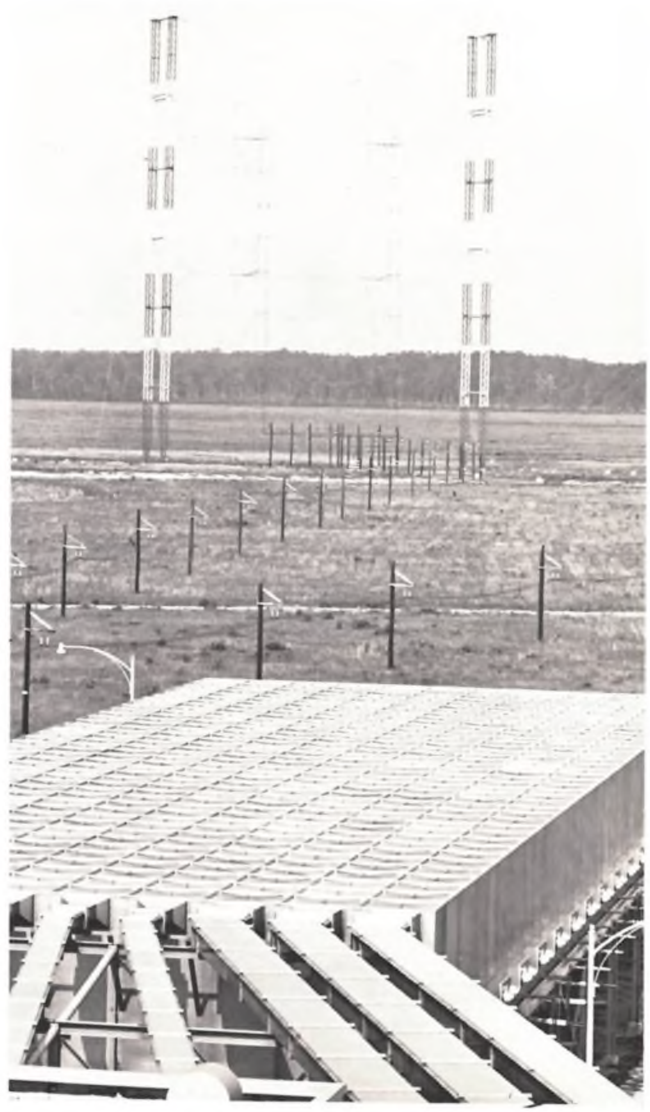
At the console of a 500 kW Continental transmitter, adjustment is made for the desired operating power — in this case, as shown below: 15 kV, 52 amperes. Continental Electronics Doherty's similar to this are in service for the VOA both here and in Europe. At Munich, for example, a 1 megawatt (carrier power) transmitter using ML-5682's has been in service for nearly 15 years. (An extensive description of this transmitter may be found in CATHODE PRESS, Volume 10, Number 1, 1953.)

Control panel of the General Electric vapor-cooled 250 kW transmitter. Extremely compact for its power capability, this new transmitter employs five ML-7482 triodes; two as modulators, one in the second intermediate power amplifier position; and two as rf power amplifiers. (An extensive description of this transmitter may be found in CATHODE PRESS, Volume 19, Number 1, 1962.)



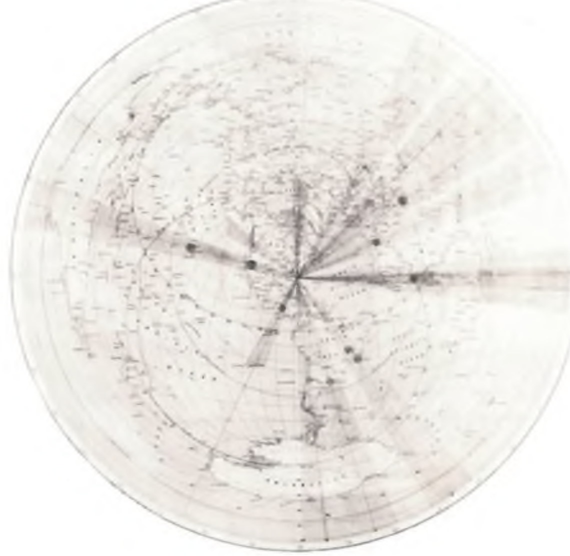
To keep the nation's largest station on the air requires a substantial inventory, one which includes, in addition to the electron tubes shown here, over 10,000 different items, among the more unusual of which are: snake bite kits, herbicides, Poison Ivy salve, gas leak detectors, underground metal detectors and aspirin.

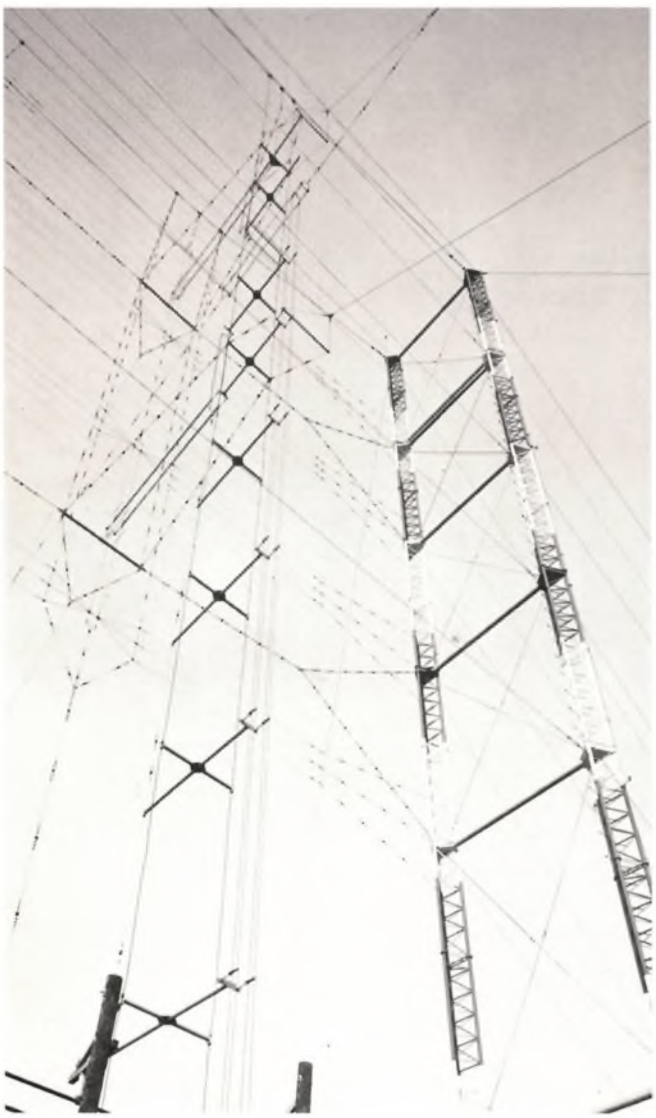
Input end of the massive rf switchgear unit. There are 11 inputs, 39 outputs arranged such that over 850 switching combinations may be made. As previously mentioned, the switchgear is controlled from the transmitter Control Console in normal use; manual operation is also possible. Interlocking controls prevent dual energizing of an operating antenna and preset facilities prevent presetting an antenna to more than one transmitter. Once properly preset the selected antenna position may be operated individually from each transmitter — or antennas may be switched as a group. . . . Antenna switching may occur without reference to "off-on" transmitter controls, since interlocks will remove plate voltages from a transmitter before an rf switch opens the antenna load and will automatically restore plate voltage when another automatic switch closes to another antenna load.



Operating high power transmitters at high modulation levels requires not only extreme care in routine maintenance, but devices in depth to prevent destructive power breakdowns. For example, negative modulation is measured (95% max.); as a result 100% positive modulation is seldom reached. Reflectometers provide carrier cutoff should the VSWR exceed a predetermined level. Over current relays and/or crowbar units dump high power energy before it can cause damage. . . . Feeder lines carry the final rf power to the antenna field, with little loss, despite maximum runs of a mile or more.

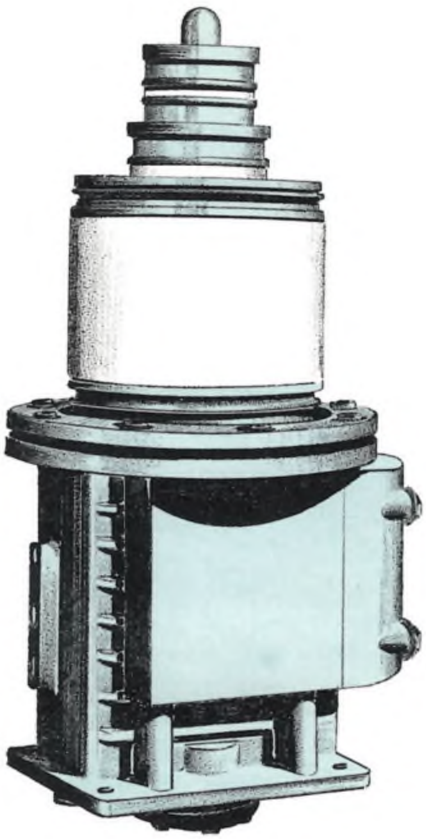
The strong signal from Greenville, North Carolina reaches Europe, Africa, the Near East and South America. A flexible relay system to overseas bases, direct shortwave to communications "targets," and an emergency communications system, Greenville-VOA is an exceedingly important installation. But it is by no means the only one in the VOA's world wide network which consists now of 87 transmitters, 55 of which are overseas with those in Germany, the Philippines and Okinawa being megawatt installations. Expansion has occurred at points other than Greenville. New antennas provide a five-fold increase for East German coverage. A major relay station has recently been completed in Monrovia, Liberia. It uses six General Electric vapor cooled transmitters of the type employed at Greenville. . . . Photograph shown at right depicts Greenville coverage chart.

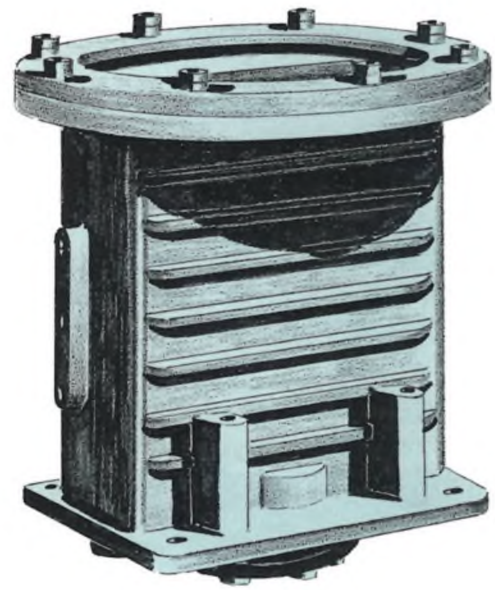




Up four hundred feet to the top array of a large curtain antenna, the signal leaves Greenville for the eastern hemisphere — from Greenland, north, to western Russia, and south nearly to the Antipodes in South America. . . . These were the reports when the first signals went out, just under 3 years ago: From Buenos Aires, Argentina: "Intelligibility good, signal strength strong . . ." And from Belgrade, Yugoslavia, ". . . clearly above normal levels." From Rabat, Morocco: "The new Greenville transmitter is coming into Rabat clear as a bell, almost booming in. It is a signal which at last holds its own with Moscow . . ." And it has continued to do so since.

The ML-8618 Triode —





Introduction

The ML-8618 triode is a new addition to the line of Machlett's high power, general purpose power tubes, incorporating the unique magnetic beaming design, which results in minimum drive requirements, high power gain, and high overall operating efficiency. Typically, the intercepted grid current of this tube at a given operating point, is about 3% compared to about 25% as found in conventional power triodes for the same power level.

The ML-8618, when operated as a Class C amplifier or oscillator, is capable of continuous output in excess of 200 kW with only about 700 watts of grid driving power. This compares to about 7000 watts for a conventional triode with similar output. The tube may be operated at full ratings up to frequencies of 50 Mc. When used as a switch tube in hard tube pulse modulators for radar, particle accelerators or similar applications, the tube may be operated to 50kVdc, delivering a pulse output of more than 8 megawatts with less than 16 kilowatts of drive power; i.e., a power gain of 500. The tube may be operated to pulse widths of 10 milliseconds and a duty factor of .06.

The water cooled anode of the ML-8618 is designed to dissipate 80 kW maximum continuously, and in excess of 100 kW for short periods. The maximum grid dissipation rating is 500 watts which is quite adequate for magnetically beamed tubes of this type.

The permanent magnet which is attached to the water jacket is highly reliable and should last for the life of the equipment. The tube has already found application in pulse modulator service, and tests as a power amplifier in Class C operation have demonstrated that continuous power output in excess of 225 kW can be readily obtained.

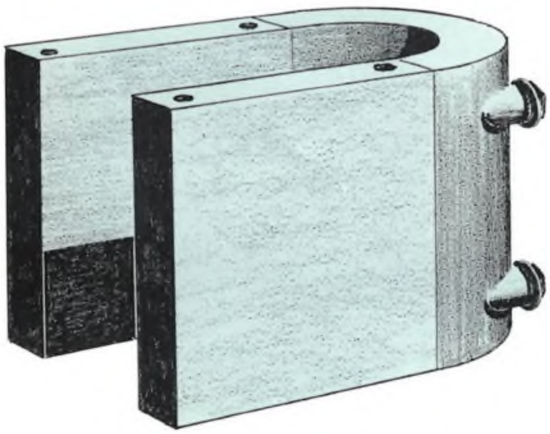
Design

In a magnetically beamed tube, electrons emitted from the cathode bypass the grid structure and almost the entire emitted current reaches the anode, thereby greatly minimizing grid drive power and grid heating. The significant point in magnetically beamed tubes is that any electrons which have been emitted from the side of a filament wire and are traveling in a direction towards the grid rod, and at an angle to the uniform magnetic field, will be forced by the magnetic field into helical paths which will keep them confined in a beam. This beam will pass between the grid rods with considerably less interception by the grid than without a magnetic field. Without a magnetic field this structure functions like a normal triode with intercepted grid currents amounting to about 25%[2].

Conventional triodes use the familiar concentric cylindrical structure in which the cathode wires are arranged on a cylindrical array surrounded by a concentric cylinder of grid wires. In this construction a little better than 50% of the filament surface area is directly facing the grid wires, the remaining filament surface area being shielded by its own curvature. To draw current from this shielded portion of the filament, considerably more positive grid potential is needed which in turn results in greater grid current inter-

A Magnetically Beamed General Purpose Power Tube

by ERICH PETER, Development Engineer, and
HELMUT LANGER, Senior Development Engineer



ception. This reduces operating efficiency and produces grid heating. Considerably less than 100% of cathode surface area will actually be utilized when optimum operating conditions persist. (See Figure 1.)

In the construction of the ML-8618, the electrode structure is arranged in parallel planes, consisting of the cathode wires, two arrays of grid rods, and the anode plates. With this arrangement, there is no "back side" of the cathode wire and almost 100% of the cathode surface area is actually facing the grid and anode (see Figure 2) [2]. The grid is constructed from heavy Molybdenum rods which support and align the cathode wires in their correct position (see Figure 3). The use of large diameter grid rods for the construction of the grid increases the thermal capacity and subsequently minimizes rise in grid temperature during long pulse operation. With this electrode configuration and the use of a magnetic field of sufficient strength, anode to grid current ratios of 100 to 1 may be achieved. For practical purposes ratios of about 50 to 1 give very high efficiency operation in most applications.

Two electrode configurations for magnetically beamed tubes have been developed. In one the use of concentric anodes, whereby the cathode-grid cylindrical structure is positioned concentrically between the inner anode cylinder and the outer anode cylinder has proved to be an optimum design for large diameter tubes, but restrictions of anode cooling and positioning of magnetic material in smaller size tubes prohibited this design for use in the ML-8618. The use of concentric anodes has been used with considerable success in the magnetically beamed, super-power ML-8549 which can deliver more than 60 megawatts of pulse power with approximately 100 kW drive power operating with a plate efficiency in excess of 90% [1]. In the alternative design investigated, flat plates were utilized for the anode. When flat plates are employed for anodes in conjunction with cathode and grid segments consisting of parallel planes, cooling can be accomplished by normal methods and the positioning of magnetic material does not present a major problem. Cooling fins have been provided within the flat anode plates (see Figure 4). These fins facilitate heat transfer from the flat anode to the cooling media and increase the mechanical strength of the unsupported flat surface. The heavy wall high conductivity copper gives good thermal capacity which allows the anode plates to withstand momentary high thermal overloads. Complete assembly is shown in Figure 5.

Tube Characteristics

The constant grid voltage characteristics of the ML-8618 are shown in Figure 6. Points "A" and "B" indicate typical operation values for pulse modulator service, as will be discussed in a later paragraph. The constant current characteristics as illustrated in Figure 7, show a typical load line for Class C oscillator or amplifier service which again is discussed in more detail in a later paragraph. In general, the characteristics are similar to those obtained in conven-

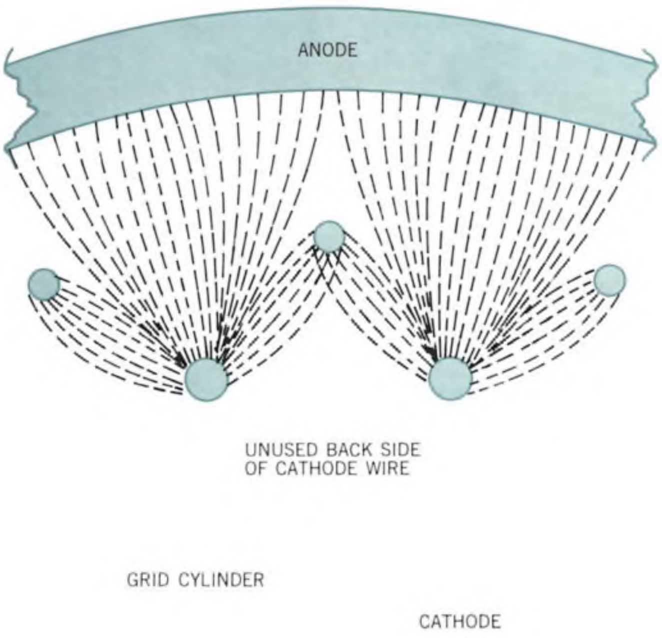


Figure 1 — Conventional Electrode Structure Showing Approximate Use of Cathode Emissive Area.

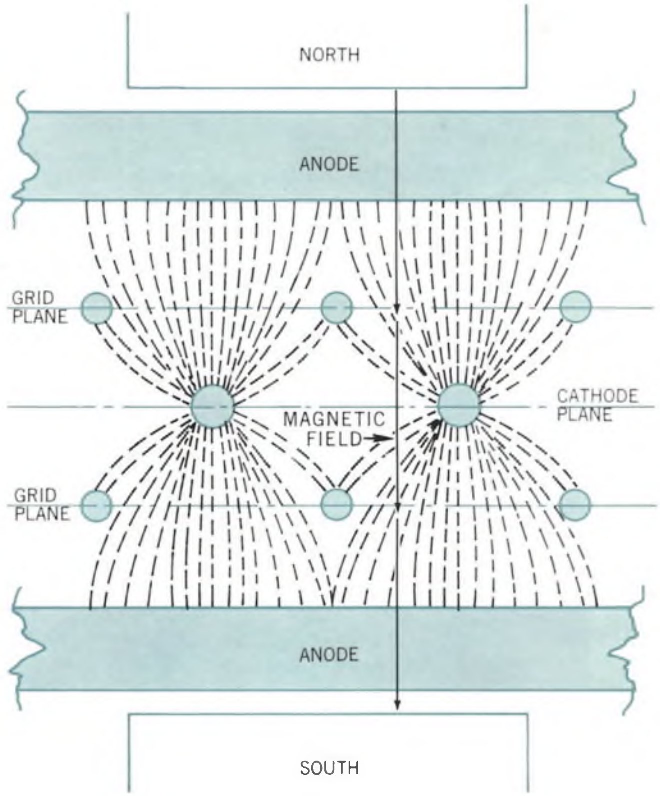


Figure 2 — ML-8618 Magnetically Beamed Electrode Structure Showing Approximate Use of Cathode Emissive Area.

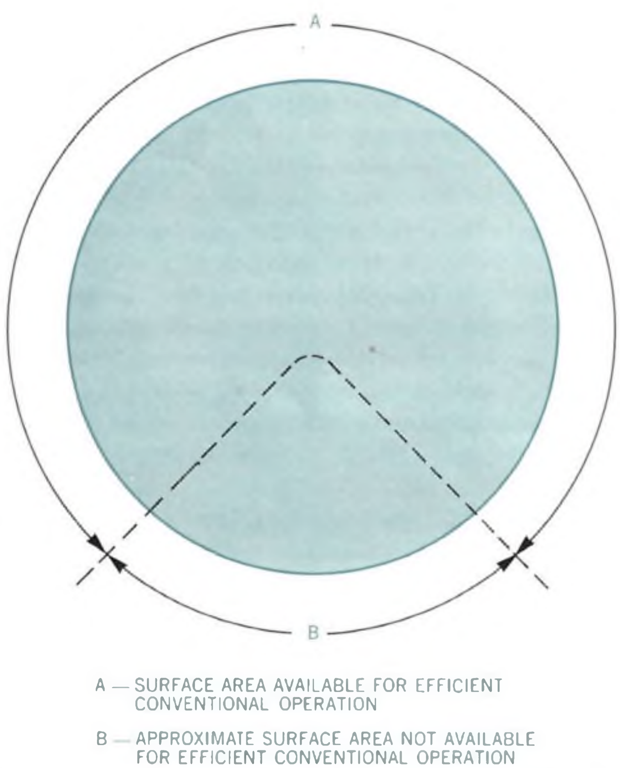


Figure 1A — Cathode Wire from Conventional Electrode Structure.

tional triodes, with the one important exception; namely, that intercepted grid current is smaller by a factor of about 10. This, of course, means that grid drive power to obtain a specific power output under most operating conditions, is drastically reduced giving the tube a relatively high power gain.

With a maximum grid dissipation rating of 500 watts and a plate dissipation rating of 80 kW, the unique anode design of the ML-8618 allows short time overloads in excess of 100 kW.

Figure 8 shows the actual measured bias voltage (when plate current equals 20 mA) and the recommended grid bias voltage vs plate voltage to 50 kV. Data are based on an amplification factor of about 16 under cut-off conditions. The plate leakage currents at 50 kVdc on the plate and —1000 volts on the grid is in the order of 1 to 2 mA. The strapped resonant frequencies for the ML-8618 are approximately 123 Mc and 138 Mc for the grid-cathode and grid-plate respectively. These measurements were made with a grid-dip meter by connecting the proper electrodes over the shortest possible paths using a conducting foil which completely surrounded the insulator.

The interelectrode capacitances of the ML-8618 tube, measured at the appropriate terminals are:

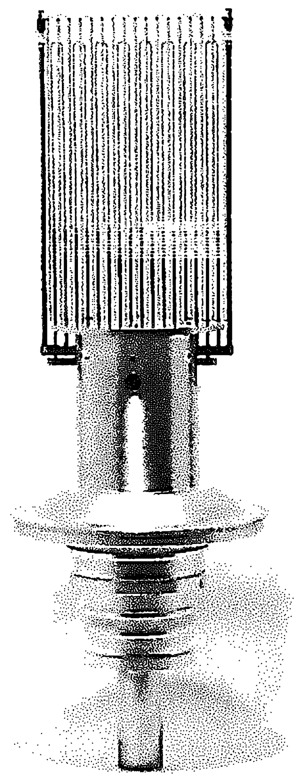


Figure 3 — Cathode-Grid-Terminal Assembly of ML-8618.

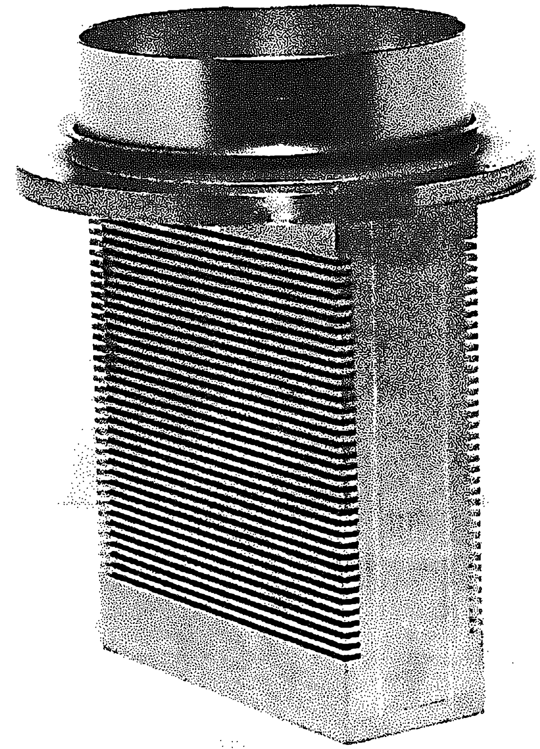


Figure 4 — Anode Assembly for ML-8618 Showing Cooling Fins.

Grid-Plate	50 pF
Cathode-Plate	9.3 pF
Cathode-Grid	145 pF

Tube Applications

Pulse Modulator or Pulse Amplifier

With the aid of the constant grid voltage characteristics in Figure 6, points "A" and "B," a typical pulse modulator application, resulting in switching power of about 7 megawatts at .06 duty is tabulated below:

Plate Voltage	E_{bb}	= 50 kV
Plate Drop	e_b	= 3 kV
Load Voltage	e_L	= 47 kV
Plate Current	i_b	= 150 amps
Cut-Off Voltage	$-E_c$	= 4000 volts
Positive Grid Drive Voltage	e_{gk}	= 1500 volts
Grid Current	i_c	= 2.4 amps
Power Output	P_o	$= i_b \times e_L = 7.05$ Mw
Plate Dissipation	P_A	$= i_b \times e_b \times$ duty = 27 kW
Peak Grid Drive Power	P_{gr}	$= i_c \times (e_{gk} + E_c) = 13.2$ kW
Grid Dissipation	P_g	$= i_c \times e_{gk} \times$ duty = 216 watts
Switch Efficiency	P_o^1/P_i	= 94 percent
Power Gain		$= 7.05$ Mw/13.2 kW $\cong 500$

Under these operating conditions, the tube may be operated in air or other dielectric medium. Pulse length of 10 milliseconds may be used as long as the maximum duty factor of 6% (.06) is not exceeded.

At nominal filament voltage, $E_f = 7.5$ volts, the maximum pulse current, which may be obtained from the cathode of the ML-8618 tube is about 200 amperes. Under such conditions, the tube should have a cathode life expectancy of more than 10,000 hours. If one requires more cathode current, the filament voltage may be increased by about 5% to 10%, which will provide cathode currents of about 250 to 300 amperes. Under such conditions the cathode life still will be several thousands of hours, which in many applications may be completely satisfactory.

In any pulse modulator application, observance of maximum tube ratings is required. In practical application, one should be conscious of possible circuit transient conditions and allow for their peaks, to guarantee that the maximum tube ratings are not exceeded. The use of fast-acting crowbar circuits, which will remove energy from a flash arcing tube to a shunting circuit is positively required[3, 4].

However, the unique grid design of the ML-8618 tube, which employs heavy grid rods of about .070" diameter, will be much less apt to be damaged by flash arcing in the tube, as might be the case in conventional tubes, in which the grid wires are considerably thinner; i.e., between .012" and .030".

Figure 5 — Complete ML-8618 Showing Large Anode to Grid Seal Area.

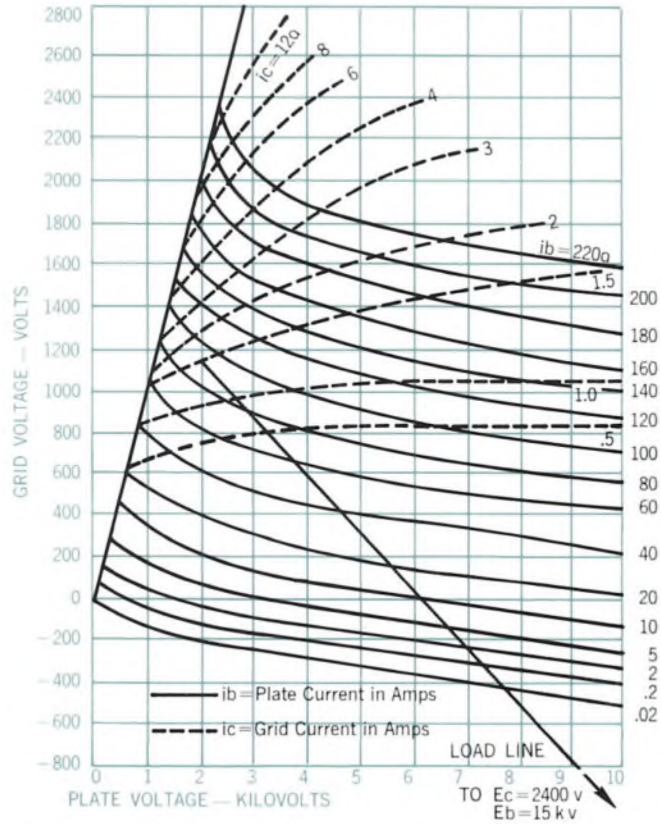


Figure 7 — Constant Current Characteristics for the ML-8618.

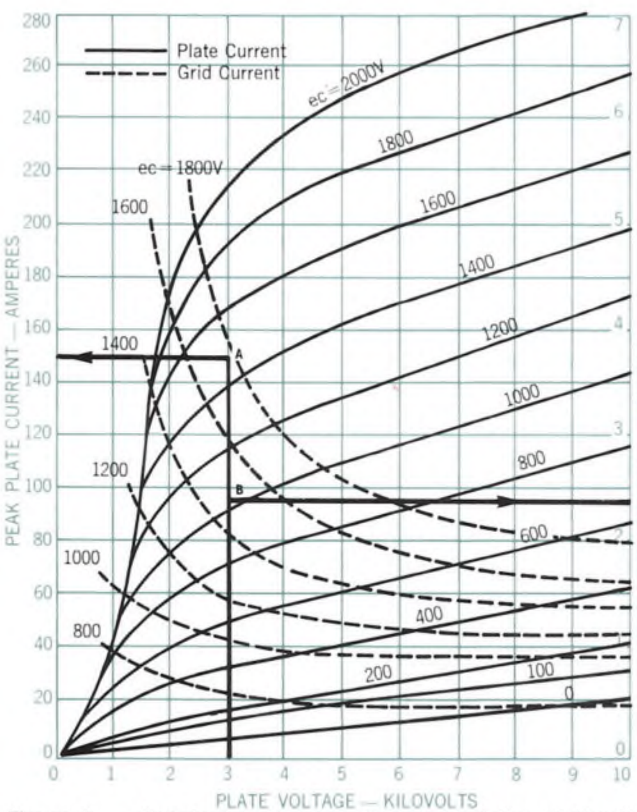


Figure 6 — Constant Grid Current Characteristics of the ML-8618.

The voltage stability of magnetically beamed tubes is generally similar to conventional tubes and primarily controlled by electrical field gradients, which are not affected by the magnetic field.

The ML-LPT-14 tube[2], which is the prototype of the ML-8618, is being used in a 40 kilovolt, 125 ampere hard tube modulator for accelerator service, at the Los Alamos Scientific Laboratory. The tube provides an output of close to 4 megawatts at .06 duty into the load with only 10 kW of driving power[5].

In a new test modulator under construction at the same laboratory, two ML-8618's will be used for a 300 amperes — 25 kV pulse modulator. Some test runs at 150 A pulse current per tube, 500 usec pulse duration and 6% duty have been already completed. Results from these test runs indicate satisfactory performance.

RF Power Amplifier or Oscillator

The ML-8618 is readily capable of generating an output in excess of 200 kW with the plate efficiency approaching 80% when operated in Class C conditions. Typical operating conditions for 200 kW output are tabulated below and the appropriate load line is shown in the constant current characteristics in Figure 7.

DC Plate Voltage	15 kV
DC Grid Voltage	—2400 volts
Peak RF Plate Voltage	13 kv

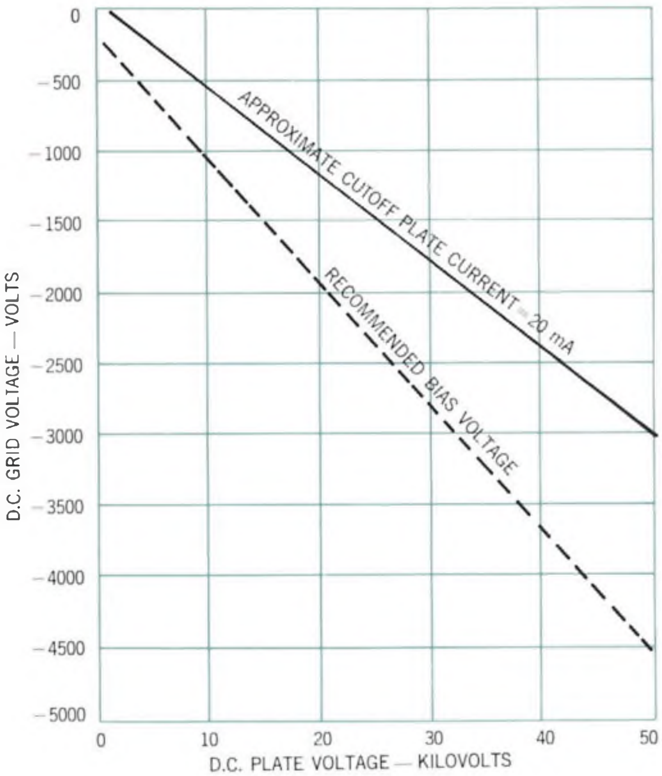


Figure 8 — ML-8618 Actual and Recommended Grid Bias Voltage for Cut-off in Inter-pulse Interval.

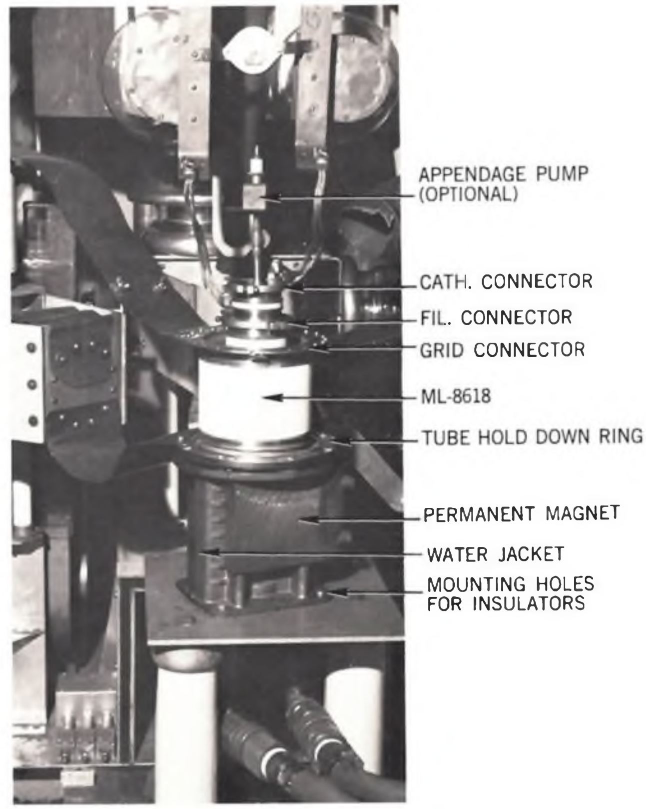


Figure 9 — ML-8618 is Shown in the Machlett 1.2 Mw Test Equipment.

Peak RF Grid Voltage	3500 v
DC Plate Current	17 amps
DC Grid Current (approx.)	.2 amp
RF Load Resistance	420 ohms
Drive Power (approx.)	700 watts
Grid Dissipation	220 watts
Plate Dissipation	55 kW
Power Output	200 kW
Plate Efficiency	79%
Power Gain	285

A comparable load line for a conventional triode of the same filament power and about the same amplification factor would give a power gain which is smaller by a factor of approximately 10. Practically such an operation could not be implemented in the conventional triode, because the high grid currents would lead to prohibitive levels of grid dissipation.

Of course, the ML-8618 may be used in other operating modes such as in Class AB single ended tuned circuits, or in push-pull arrangements as in audio generators as long as the operating parameters are held within the limits of the maximum tube ratings.

Again, in any application in which considerable power is involved, the use of a crowbar is necessary. Load arcing may set up transients, which in turn can cause breakdown in the tube and the dumping of excess circuit energy into it if energy diversion is not handled fast enough[3, 4].

Figure 9 shows the ML-8618 tube under rf test in the Machlett 1.2 Mw rf test unit. The tube is here tested under Class C amplifier conditions at 13.6 Mc. ML-8618 tubes are operated in this unit to an output level exceeding 250 kW at plate voltages of 18 kV and higher. Under dc static conditions the anode of the tube is subjected to a plate dissipation of more than 100 kW. Figure 9, which illustrates tube, water jacket, magnet and tube connections as discussed later, shows also part of the circuitry. Plate-grid neutralization is shown on the left, filament by-pass capacitors are shown above the tube, while the blocking condenser and the load coupling capacitor are partly hidden by the ML-8618. Power output of the tube is determined calorimetrically by measuring the temperature rise and flow of water through a "water resistance" load[6].

Limits of High Frequency Operation Extended by ML-8618

It is well known that power tubes operated as an amplifier or oscillator are limited in power output when the frequency is raised above certain limits. The power output usually remains constant to a certain frequency level, then slowly declines until a point in frequency is reached where the power output drops rapidly. Apart from power output limitations which set in due to transit time and other effects, derating of tubes is required primarily by the increase in circulating high frequency currents through the tube, resulting in associated losses and heat generation.

For operation below 100 Mc, the tube designer is mainly concerned with the losses which will appear in the tube and has to consider all aspects to minimize such losses. Electron transit time effects are of secondary importance in this frequency range since practical electrode spacings are still compatible with electron transit time. The main limitations are found in the seal area which easily may be overheated by the large circulating currents which have to flow through the relatively lossy (I^2R) ceramic-metal seal interfaces.

In a triode, the most critical seals are the anode and grid metal to ceramic seals. The rf voltage is high between grid and anode and consequently the circulating currents are high.

In the ML-8618 the grid-anode insulator or "anode ceramic" is of relatively large diameter (see Figure 5). This design has been chosen in order to achieve a simple technical solution for the transition from the round terminal to the rectangular anode. The large diameter also gives large ceramic-metal seal areas permitting relatively high frequency limits under full voltage ratings.

The frequency limit up to which full voltage ratings apply can be determined from the rf current carrying capability of a well established tube for which practical experience exists for high frequency operation. This data can then be used to establish ratings for a new tube such as the ML-8618. Of course, the seal construction should be essentially identical for both tubes and the cooling aspects and the high frequency heating of other tube parts has to be taken into consideration. Further, since seal losses go up with the frequency, the comparison should be made preferably at the same frequency level. Alternatively, the rating could be based on practical data obtained at higher frequencies since this would merely introduce a safety margin for the new tube.

The high frequency current which flows over the anode ceramic-metal junction is governed by the expression:

$$I = 2 \times \pi \times f \times C_{g\text{-}A} \times V_p$$

where I = peak rf current in amperes
f = frequency in cycles
$C_{g\text{-}A}$ = grid-anode interelectrode capacitance in Farads
V_p = peak rf voltage in volts

With this equation and known seal diameters, it can be determined how many amperes of circulating current flow per inch of seal length in a given tube. To arrive at a conservative rating for the ML-8618, the high frequency tetrode ML-7007, which has been used extensively in television service, was chosen for comparison purposes. This tube has compression seals which are very similar to those employed in the ML-8618. The ML-7007 has a maximum

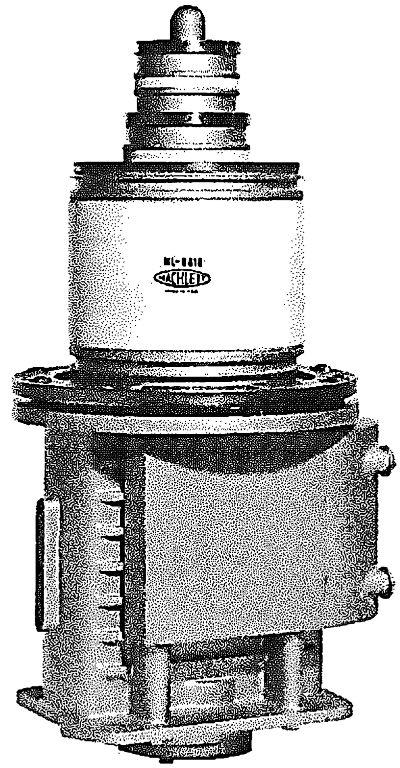


Figure 10 — ML-8618 Tube and Water Jacket-Magnet Assembly.

plate voltage rating of 7,500 volts which applies up to 220 Mc, a plate-screen capacitance of 21 pF and anode and screen grid ceramic-metal seal diameters of 4.5″. The maximum peak plate rf voltage in Class C operation will be in the order of 5,000 volts. Accordingly, the circulating current is:

$I = 2\pi \times 220 \times 10^6 \times 21 \times 10^{-12} \times 5 \times 10^3 = 145$ amperes. The current per inch of seal circumference is then:

$i = 145/\pi \times 4.5 = 10$ amps/in

If 10 amperes/linear inch is taken as the safe upper limit, the frequency limit for the ML-8618 can be established from above relations as follows:

Class C operation: peak rf voltage approx. 16 kV
grid-plate capacitance = 50 pF
seal length 7.25 Dia. x π = 22.7″

Permissible rf current: $I = 10 \times 22.7 = 227$ amperes

Maximum frequency for full voltage rating:

$$f = \frac{I}{2\pi \times C_{g\text{-}A} \times V_p} = \frac{227}{2\pi \times 50 \times 10^{-12} \times 16 \times 10^3} \cong 45 \text{ Mc}$$

Neglecting lower seal losses at the reduced frequency, the full voltage ratings for the ML-8618 should probably apply to about 50 Mc, because comparison has been made to a tube operating at considerably higher frequencies. The insulator and seal areas have, of course, to be cooled. An air flow of about 200 to 400 cfm, depending on the frequency, evenly distributed over the terminal should be adequate in order to maintain uniform envelope and seal

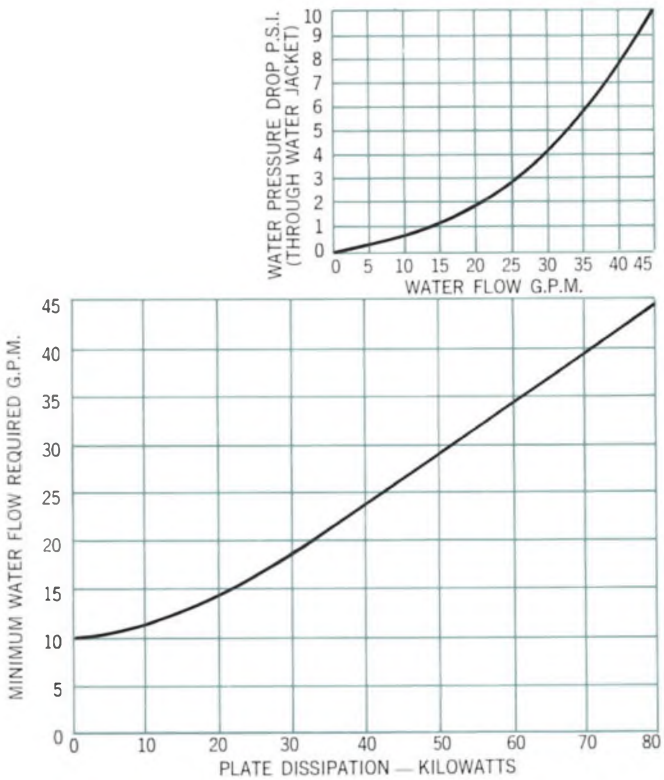


Figure 11 — ML-8618 Anode Water Cooling Characteristics.

temperatures not greater than 200°C. The above frequency limits assume also even distribution of the rf current around the circumference of the seal.

In order to utilize the tube at such high frequencies, the inductances in the tube structure had to be kept sufficiently low. This has been achieved by retaining an essentially coaxial construction and the relatively high strapped resonant frequencies (138 Mc for grid-plate and 123 Mc for cathode-grid) indicate that the tube can be used indeed at 50 Mc or higher. Of course, at higher frequencies appropriate voltage derating is required.

Tube Cooling

The power output of conventional transmitting tubes is usually limited by the grid dissipation capabilities of the specific tube type. In the magnetically beamed tubes, wherein intercepted grid currents are drastically reduced to the point where grid dissipation is no longer the major limiting factor in power output; the power output of the tube becomes dependent on the plate dissipation capability of the anode.

In a power tube, heat is liberated at the anode by the conversion of the kinetic energy of the impinging electron beam. This heat must be removed in the most efficient way so that the greatest amount of heat can be transferred with the smallest amount of water flow. Although there are a number of exotic ways of increasing heat transfer rates with water cooled tube, like subcooling of the coolant, or use of very high surface flow rates, the most economical process is still the use of a moderate water flow across extended surfaces.

On the ML-8618, a surface extension in the form of rectangular ribs has been provided on the two flat anode sides (see Figure 4). Water within the water jacket is distributed equally to these two ribbed sides and will normally maintain the anode structure at a sufficiently low temperature. This is extremely important, as the tube may, in certain applications, be subjected to varying power loads within short periods of time, and possibly even to short time overloads. The integrated water jacket, magnet assembly should give trouble free service for the life of the equipment under normal operating conditions (see Figure 10). To safeguard the water jacket and anode structure from adverse conditions, a pressure relief valve must be attached to the inlet of the water jacket assembly.

Water, because of its high heat absorbing capacity, low cost, and accessibility, is the normal coolant medium used in equipments employing tubes in the 80 kW and greater power range. ML-8618 water flow requirements for various values of plate dissipation are graphically presented in Figure 11.

Tube Variants — ML-8619, ML-8620

Variants of the ML-8618 are now in the prototype stage. These tubes are basically identical in construction, varying only in their mode of anode cooling. The ML-8619 features vapor cooling with a plate dissipation rating of about 80-100 kW, while the ML-8620 is air cooled with design plate dissipation rating of between 20 to 30 kW.

Tube Accessories

Filament connectors are provided with sufficient mounting for bus bar termination, and the control grid connector has suitable mounting for rf strap connection.

The water jacket is supplied with the tube hold-down ring which locks the tube into position with ½ turn each of eight bolts. Mounting holes for high voltage strap connections and for attachment of stand-off insulators are already incorporated in the jacket. The above connectors and mounting facilities are illustrated in Figure 9.

Outline drawings for specific dimensions are available on request.

REFERENCES

[1]Langer, H., "A Magnetically Beamed Super Power Electron Tube — The ML-8549," *Cathode Press*, Vol. 22, No. 2, 1965.

[2]Randmer, J. A., "Magnetic Beaming in Power Tubes," *Cathode Press*, Vol. 22, No. 2, 1965.

[3]Doolittle, H. D., "Vacuum Power Tubes for Pulse Modulation — Part II," *Cathode Press*, Vol. 21, No. 2, 1964.

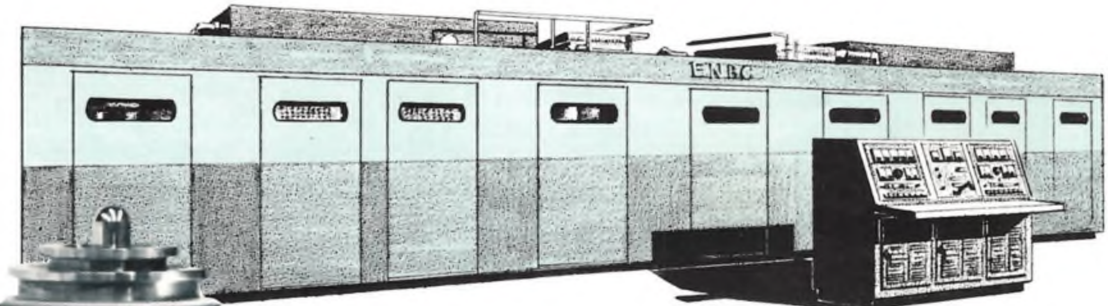
[4]Singer, B., "Flash Arcing in Power Tubes Due to Circuit Excited Transients," *Cathode Press*, Vol. 22, No. 1, 1965.

[5]Freyman, R. W., "A 40-Kilovolt, 125-Ampere Hard Tube Modulator for Accelerator Service," *IEEE Transactions on Nuclear Science*, Vol. NS-12, No. 3, June 1965.

[6]Wilson, T. L., "Design, Engineering and Construction of the Thermex High-Frequency Tube Tester," *Cathode Press*, Vol. 20, No. 1, 1963.

Editor's Note:
Two Continental Electronics Model 319 Transmitters, installed in Enugu, Nigeria, are now in operation. Ordered by the government owned station, these 250 kW units are to be used to provide an expanded program of education for the Nigerian people. Enugu adds to the long list of global transmitters using Machlett electron tubes.

A 500 Kilowatt



Continental Electronics recently completed the design and manufacture of a 500 Kilowatt Medium Wave Broadcast Transmitter for Eastern Nigeria Broadcasting Corporation. This transmitter embodies certain design techniques and circuitry which result in compact size, high power efficiency and reliable high quality performance.

The design centers about a new high efficiency screen modulated amplifier[1] used in new 50 and 100 kW standard broadcast transmitters built by Continental. Nigerian specifications required the combining of two completely independent 250 kW transmitters (illustrated above) each of which use the recently introduced high power tetrode, the ML-8545 (at left).

In addition to high efficiency screen modulation, several other factors of design interest — as noted below — are associated with the new transmitter and will be discussed in this article.

1. A low loss output tank circuit utilizing a toroidal tank inductor.
2. Inductive coupling to this tank circuit which allows the use of a simple series combining circuit for transmitter output.
3. Vapor phase cooling of the power amplifier stage.
4. The application of silicon rectifiers in all transmitter power supplies.

The high efficiency screen modulated amplifier, conceived two years ago, combines the principles of simple screen grid modulation with the Doherty linear amplifier.

[1]U.S. Patent applied for.

Medium Frequency Standard Broadcast Transmitter

by JOSEPH B. SAINTON, Senior Engineer, Communications Section
Continental Electronics Manufacturing Company

The greatest disadvantage of conventional screen modulation is its low power efficiency. The reason for the low plate efficiency of the rf output or modulated stage, is the rf plate voltage swing must be restricted to one-half its maximum value at carrier level so that it can be doubled to produce 100% amplitude modulation. Since plate efficiency is roughly proportional to rf plate voltage swing and since modern tetrodes are capable of 80% plate efficiency in Class "C" operation, then a plate efficiency of 40% at half plate swing can be expected. With 100% sine wave modulation, since plate input power doesn't change with modulation, this increases to 60% average efficiency because power output increases one and one-half times. At 100% modulation, the overall transmitter power efficiency is comparable to other modulation techniques. Some advantages of screen modulation are:

1. Very low modulator power requirement.
2. No modulation transformer is needed, which allows for the use of rectified rf envelope feedback around the audio stages to correct for noise and non-linear distortion arising in the modulated amplifier.
3. Reduction to about one-half the peak rf and dc voltage applied to the modulated amplifier compared to plate modulated amplifiers of the same power output.

Screen Modulation

It has been said that screen modulation is incapable of producing 100% negative modulation, or complete carrier cut-off. This misconception has probably arisen by comparing screen modulation to plate modulation where carrier cut-off is achieved by modulating the plate voltage to zero volts. By direct comparison a screen modulated amplifier will not modulate 100% by reduction of screen voltage to zero volts, but by swinging the screen slightly negative, 100% modulation is easily achieved. This negative excursion is generally about 10 or 15% of the peak to peak audio screen voltage required for 100% modulation. Moreover, the rf plate swing varies in linear fashion with these screen voltage excursions down to within about 5% of peak to peak screen voltage near cut-off. This means that up to 95% modulation, the stage is linear but will have a slight rounding of the negative peak from 95 to 100% modulation. This rounding increases harmonic distortion by 0.5% at 100% modulation and is completely eliminated by overall feedback.

The Doherty Amplifier

The Doherty high efficiency linear amplifier which has been in use for over thirty (30) years, has two very distinct advantages over high level plate modulation for high power applications.

1. It requires no modulation transformer which is not only very costly but presents some very formidable design considerations with respect to performance and reliability.
2. The voltage applied to the anode of the modulated amplifier of a plate modulated stage is almost twice that applied to a Doherty amplifier of comparable power output at 100% modulation.

The New Amplifier

The recent development of tetrode tubes having plate dissipation in excess of 10 kw led to the feasible application of a circuit combining screen modulation with the Doherty amplifier at high power levels. In this circuit, the Doherty amplifier is screen modulated rather than operated as a linear amplifier of a modulated wave. The Doherty linear amplifier which used triode tubes required that the carrier tube be operated Class "B" so that the negative peak of the modulated driving wave would be amplified without distortion. This limited the plate efficiency to about 66%. In addition to this, grid swamping was required because of the load changes presented to the driver stage due to grid current fluctuations during modulation. The triode amplifier tubes required a great deal of driving power in addition to the swamping and the driver stage operated at low plate efficiency since it was usually grid or screen modulated. In the new circuit the carrier tube can be operated Class "C," since negative peak linearity depends on screen grid linearity, which as mentioned before is very good, and not dependent on control grid conditions. No grid swamping is required since modulation does not appear on the driving signal. The drive power required is a small fraction of that required for triodes and the driver stage can be operated Class "C" also. All of this adds up to high overall transmitter efficiency. By way of comparison, our new 50 kW transmitter using this circuit requires only 82 kW of transmitter input power at carrier level. Other types, including plate modulated and phase to amplitude, require from 94 to 98 kW input power.

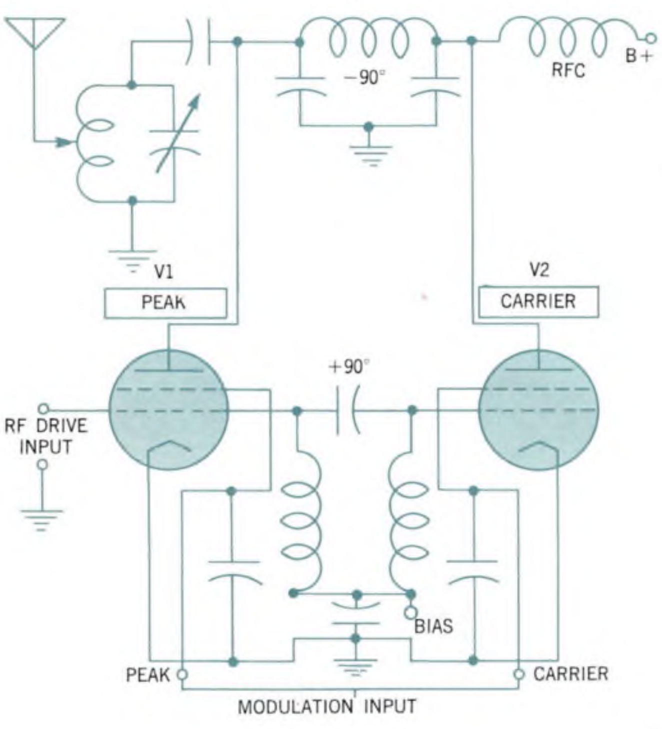


Figure 1 — Simplified Diagram of High Efficiency Screen Modulated Amplifier.

How It Works

Basically, the amplifier consists of two ML-8545 tetrode tubes with a 90° lagging network connected between the anodes and a 90° advance network between the grids. (Figure 1) At carrier level the carrier tube functions as a conventional Class "C" amplifier and as such, delivers the full carrier output power at high plate efficiency. A nominal value of positive screen voltage is applied to the carrier tube. The actual value depends on tube types and is generally one which gives a good compromise between rf drive power and modulation power required. Both tubes receive equal grid drive but the peak tube delivers no power at carrier level because its plate current is cut-off due to a negative voltage applied to the screen grid. Screen voltage is applied to both tubes through iron core chokes across which the modulating voltage is applied.

In order to understand how amplitude modulation is accomplished, first consider what happens during negative modulation. The modulating voltage appears across both screen modulation chokes. As this voltage drives both screens negative, nothing happens to the peak tube because it is already cut off. The carrier tube, however, will be driven toward cut-off in a linear fashion until the instantaneous screen voltage is slightly negative, at which time plate current cut-off will occur. This is the negative peak of 100% modulation.

What happens on positive peaks of modulation is slightly more involved. First, we must understand the basic operating principle of the Doherty amplifier.

The carrier amplifier is operating at full carrier output power at high plate efficiency as a Class "C" amplifier. This means that its plate voltage swing is maximum, or, in other words, its minimum plate voltage is very close to its instantaneous screen voltage. There are only two means by which more power can be taken from the tube. One would be to increase its dc plate voltage with an accompanying increase in rf plate voltage swing as is done in plate modulation; and the other is to decrease its plate load impedance while maintaining the same plate swing. This is what is accomplished by the action of the peak tube and the 90° network which separates the anodes of the two tubes.

In order to establish a clearer picture of the operating condition for the amplifier, let's assign values to a hypothetical design.

Suppose we design a 50 kilowatt amplifier. Let's use a dc plate voltage of 16 kV and establish $E_{b\ min}$ at 1860 volts. Our peak plate swing will then be 14,140 volts, or 10,000 volts rms. In order to take out 50 kW, this 10 kV rf voltage must appear across a plate load impedance of

$$R = \frac{E^2}{P} = \frac{10{,}000^2}{50{,}000} = 2000 \text{ ohms.}$$

At modulation crest condition, a 50 kW amplifier will have a peak envelope power output of 200 kW since carrier

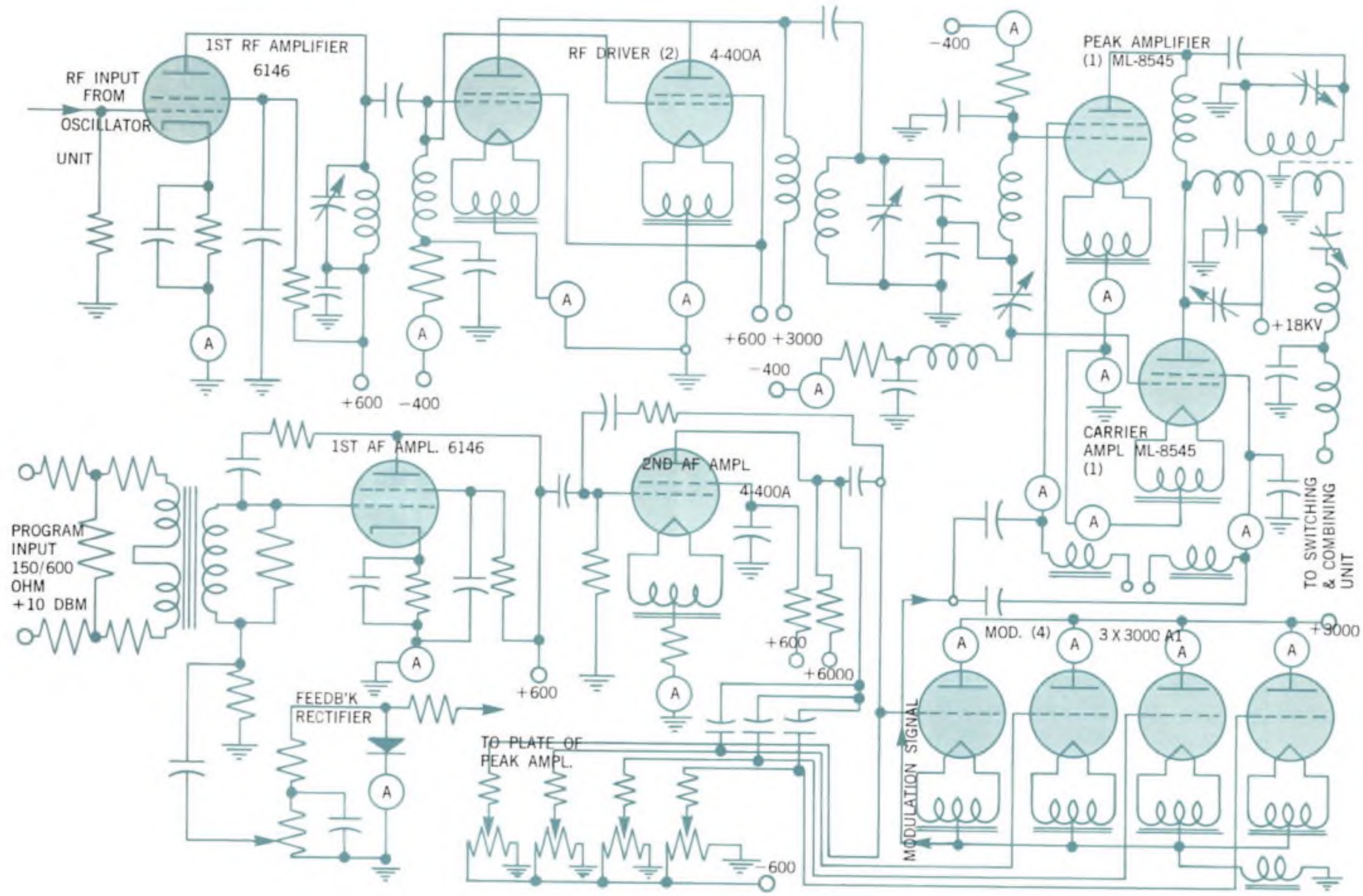


Figure 2 — Simplified Schematic 250 kW MF Broadcast Transmitter.

level voltage and current are both doubled. For two tubes in parallel this would mean that each should supply half of this, or 100 kW at crest. The carrier amplifier plate load impedance must therefore be halved, or reduced to 1000 ohms at crest. The other tube, or peak amplifier must also work into a 1000 ohm load at crest. This is where the 90° interplate network comes into the picture.

If we arrange the peak amplifier tank circuit to transform the antenna load to 500 ohms at the plate of the peak tube and arrange the 90° interplate circuit to transform the 500 ohm load up to 2000 ohms at the plate of the carrier tube, let's see what happens at crest condition.

As the modulating voltage drives the peak tube screen voltage in a positive direction, the tube begins to draw plate current and delivers power into the 500 ohm plate load impedance. At crest condition the screen voltage is high enough so that the peak tube plate swing is also 10 kV rms, the same as the carrier tube. But although the load impedance at that point is 500 ohms, the peak tube thinks it is 1000 ohms because the carrier tube is delivering an equal amount of current into the load. This is analogous to two batteries of equal voltage in parallel across a common load resistance. The actual load may be 500 ohms, but since each battery is supplying only half the load current, the load looks like 1000 ohms to each one.

The 90° interplate network has the well known property of quarter wavelength lines; that is, an impedance inverting characteristic such that what is done on one end brings about an exact opposite change on the other end. So, since the 500 ohm load on the peak tube end now looks like 1000 ohms, or twice 500 ohms, then the 2000 ohms at the carrier plate now looks like half of 2000 ohms, or 1000 ohms. Therefore, each tube is delivering 100 kW into 1000 ohms at a plate swing of 10 kV rms at crest condition.

Each of the two 250 kW amplifiers uses a pair of Machlett Type 8545 vapor cooled ceramic tetrodes, one peak tube and one carrier tube. (Figure 2) These tubes have a plate dissipation rating of 150 kW, but operate at only about half this in the high efficiency amplifier. The tubes are operated at a dc plate voltage of 18 kV, a carrier amplifier screen voltage of 1500 volts and were driven to full power output of 250 kW with only about 600 watts of grid drive per tube. They were screen modulated by four Type 3X3000A low mu triodes connected in parallel in a cathode follower configuration. The rf driver tubes are a pair of 5CX1500A's in parallel driven by a single 6146 beam tetrode which was driven from the oscillator unit located in the console.

Vapor Cooling

The vapor phase cooling system has proved to be a very compact and reliable means for removing the anode dissipation heat from the power tubes. There are several vapor cooling configurations in present use, the two most popular being the vapor down and vapor up techniques. In the vapor up system, the anode of the tube is immersed in a pot of water. The steam given off by boiling escapes out of a Pyrex pipe set to one side of the top of the boiler. The steam rises up the pipe into a radiator. Air blown through the radiator condenses the steam back to water which is returned to the boiler through a series of electric valves and level controls. A small reservoir, generally only 4 or 5 gallons, feeds water into the system as required by loss due to evaporation into atmosphere since the radiator is vented to ambient air to prevent excessive pressure rise. This system requires no pump and is very compact.

The vapor down system, which was selected for use in this transmitter, is quite similar, except that it requires a small pump to replenish the boiler water. We chose this system for two reasons; one, it allows a greater degree of flexibility in cooling system layout and, secondly, the absence of the steam pipe out the top allows for a better isolated rf input circuit layout. This is important when working with high gain high power tetrodes.

Vapor Down

In this system, a boiler having another inner container, or weir is used. (Figure 3) Water is pumped into this inner weir by a small pump at only about 2 or 3 gallons per minute. The overflow water and steam escape through an outlet in the bottom of the boiler and into the water storage tank. The steam flows out a pipe in the top of the tank to the steam condensing radiator. Condensate from the radiator is returned by gravity flow to the water tank. In this transmitter the steam condensing radiator is mounted on top of the cabinets. Cooling air is blown into the cabinets and exhausts through the radiator in the roof. The water tank, pump and all plumbing is located in the transmitter cabinets.

A problem encountered in vapor-down systems is the ability of the water pump to maintain its pressure and flow characteristics while pumping water at or near boiling temperatures. Several solutions are available; one being to mount the pump in a pit 5 or 6 feet below the water tank in order to maintain a high water pressure on the pump inlet. This solution has some disadvantages; it requires excavation of a pit and makes the pump and associated plumbing very inaccessible for maintenance.

An alternate solution is to cool the storage tank water to a few degrees below boiling temperature by mixing cool water with the boiling water fed to the tank from the boilers. This

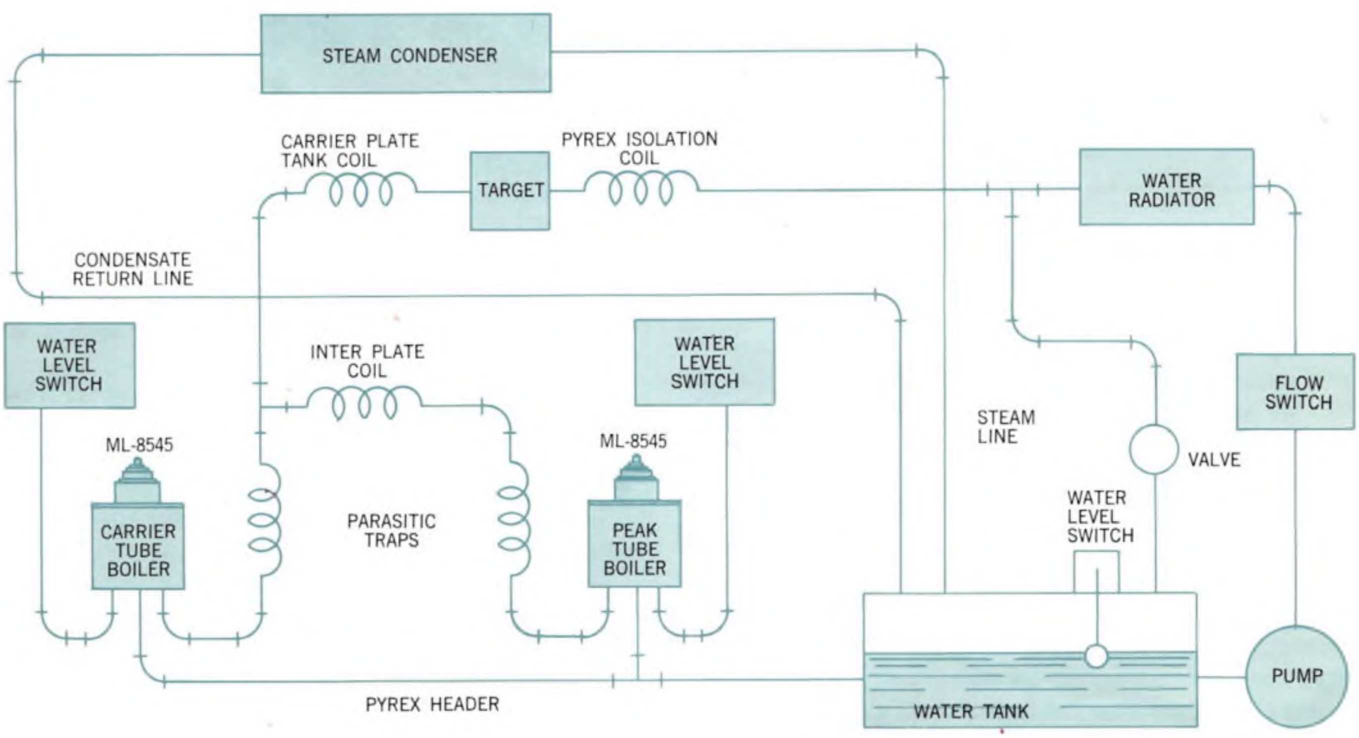


Figure 3 — Vapor Cooling System for 250 kW MF Broadcast Transmitter.

was the technique we chose to use on this transmitter. The pump inlet was connected directly into the side of the water tank. Water out of the pump was fed to a small water radiator mounted on the roof of the transmitter cabinets. Some of the air blown into the cabinets was exhausted through this radiator. About 15 GPM of the cool water out of this radiator was fed back into the water tank. Another 8 GPM was fed through the interplate inductor and carrier plate inductor into the power amplifier boilers. From a cold start; that is, with storage tank water at ambient temperature, the cooling system would become temperature stabilized after about one-half hour running at full power output. The storage tank water would settle at about 208°F and the small radiator outlet water at about 150°F. As mentioned previously, some of this 150° water was fed to the boilers through the plate inductors. In the plate circuit configuration, these inductors made direct metallic connections to the boilers and although they didn't require water cooling, they provided a means for plumbing the inlet boiler water without having to use fragile insulated pipe, and made possible the use of only one anti-electrolysis target at the point where the dc plate voltage tied onto the plate inductor. In addition, since this point is at the cold end of the plate inductor, the length of insulating pipe to the grounded water system was about half that which would be required if an insulated feed were used directly to the boiler.

Vapor vs. Water

In gaining experience with vapor cooling systems, one has to become conditioned to the fact that parts associated with the cooling system will run hot. The hottest external metallic parts of water, or air cooled components will run at about 160°F, whereas in vapor cooling they will run at 212°F. What's more, the components used in vapor systems generally are bulkier than their water cooled counterparts. This doesn't mean to imply that the total system is more massive because it isn't — but the boiler and connecting steam pipes which are in the transmitter cubicles are bigger. These larger components will give off more radiant heat by virtue of their greater mass and higher temperatures. In order to recognize the advantages of vapor phase cooling over water cooling we need to compare the relative size of components required for each at the same power level.

First, the water cooled counterpart would require a pump that would deliver 60 to 70 GPM of water to the two tubes at a pressure of 15 to 20 pounds per square inch. The vapor system requires only about 10% of this flow and pressure with a correspondingly great reduction in pump horsepower. Secondly, since water cooled systems generally restrict outlet water temperature to about 160°F, the surface area and air flow requirements of the heat exchanger radiator are about triple that needed for vapor cooling which has entering steam temperature of 212°F. Third, because of the greater water holding capacity of the water cooled system due to large radiators and associated long pipe lengths, a storage tank of at least 500 gallons capacity would be required. For vapor cooling, a fifty gallon tank is more than adequate. The end result is a cooling system that occupies from 25 to 30% of the space volume required for water cooling with a similar reduction in pump and fan horsepower requirement. These improvements allow for more compact overall transmitter design and increased power efficiency.

Low Loss Tank Circuit

A part of the design objectives in this transmitter was high overall efficiency; that is, conversion of a great amount of the 60 cycle ac input power to rf power into the antenna. The high efficiency amplifier with its attendant requirement of low rf drive and modulator power accomplished this. In order to further improve overall efficiency, and for other reasons, it was decided to utilize a low loss toroidal tank inductor in the output tank circuit. Continental Electronics has had considerable experience in design and construction of this type inductor dating back to the early 50's when one was used in the output tank of a 500 kW low frequency transmitter. Since then, toroid coils have been designed into high power VLF and HF equipment.

The principal feature of the toroidal inductor is its high merit "Q." Helical coils as conventionally used in transmitters will usually have a "Q," that is, a ratio of reactance to resistance of about 200 for a well designed coil with adequate spacing to its shield compartment. On the other hand, a properly designed toroid will have a "Q" of 2000. Let's look at this in terms of power loss for a 250 kW transmitter.

The output tank circuit was designed for a loaded Q of 4; that is, the ratio of kVa over kW of the parallel resonant circuit, not to be confused with the merit Q of the tank coil and condenser. At this value of loaded Q, the tank circuit has a circulating current of 184 amperes at carrier level. The inductive reactance of the required coil is 30 ohms. The equivalent rf resistance of a helical coil having a merit Q of 200 will therefore be:

$$R = \frac{X_L}{Q} = \frac{30}{200} = .15 \text{ ohms.}$$

The power loss of this inductor with a circulating current of 184 amperes will be:

$$184^2 \times .15 = 5100 \text{ watts.}$$

The toroid inductor having a merit Q of 2000 will therefore have a power loss of one-tenth of 5100 watts, or 510 watts. Since the difference is about 4600 watts and is obtained at 75% plate efficiency, then a reduction in transmitter input power of 6150 watts is achieved by using the toroidal coil.

The heat given off by the helical coil would require water cooling, whereas the toroid coil with only 510 watts loss, runs cool with only convection cooling.

Another great advantage of the toroidal inductor is that it can be mounted in close proximity to grounded panels and shields without affecting its inductance or power loss. A fully shielded helical coil would require a much larger cabinet enclosure.

Output Combining

In combining the rf outputs of two amplitude modulated transmitters, there are several factors to be considered. First, does the reliability specification dictate the use of one which allows uninterrupted service in the event of failure of one transmitter? Second, is a five or ten second interruption with service restored at half power as good or as bad as no interruption but with a reduction to 25% power? The answers to these are ordinarily spelled out in the customer's specification. Generally speaking, there are two types of combining circuits — those which completely isolate one transmitter from the other and those which do not. The ones which don't are quite simple in form since they merely connect the outputs either in series or in parallel. The circuits which provide isolation take the form of hybrid rings and bridged tees and therefore require more coils and condensers and also require a "waster" or balance resistor. This resistor is necessary to provide the proper load impedance to one transmitter in the event of failure of the other transmitter. Since this resistor effectively parallels the antenna load, half of the output of one transmitter goes into this load when the other is inactive. When both transmitters are in service at equal output voltage and in phase, no power is delivered to the balance resistor.

Transmitters in Series

Some economic considerations plus the inherent simplicity of series combining dictated its use in this transmitter. Parallel combining was rejected because of the large rf currents involved in the low impedance circuits that come with high power transmitters in parallel.

In a single ended series combining circuit, the output of one transmitter has one terminal grounded but both output terminals of the other transmitter are above ground by the output voltage of the other transmitter. For this reason, it becomes necessary to use inductive coupling to the output tank circuits of the transmitters in order to isolate the "above ground" output of one transmitter from its grounded tank coil. A five turn fixed coupling loop was wound around each of the two output tank inductors with a Faraday shield between the tank inductor and coupling link to minimize capacitive coupling. This arrangement provided a 3 to 1 resistance transformation ratio; that is, a 40 ohm resistance connected across the link was transformed up to 120 ohms at the plate of the peak tube which is the proper value for full power operation. A rather simple rf switching system was devised which allowed individual or dual transmitter operation with the output links connected in series. When a single transmitter was connected to the antenna feed, the other one was automatically connected to the phantom antenna. Since with series combining the load impedance divides in half between the two transmitter outputs, it is necessary to provide two line matching networks, one to transform the 230 ohm feeder line impedance down to 40 ohms for single transmitter operation, and another to transform 230 ohms to 80 ohms for dual operation.

Identical Twins

It becomes obvious that this combining technique dictates the necessity of both transmitters coming on simultaneously since if one came on before the other, it would see an 80 ohm load rather than its proper load of 40 ohms. This problem was solved quite simply by holding off rf excitation to both transmitters until their plate voltage circuits had cycled on and then turning on rf drive to both with a single relay. Likewise, an overload in either transmitter would remove drive to both by operating this common relay.

In order to ensure the proper combining of two amplitude modulated transmitters, several important conditions must be satisfied. First, the output voltages of both must be equal in amplitude and exactly in phase. Second, the gain through the audio stages of each must be identical with respect to frequency and phase response. This is not difficult to accomplish with identical circuits even though most electrical components have ±10% tolerances. Since this type of transmitter is adaptable to the use of overall envelope feedback, then the amount of feedback must be identical for both.

A single rf oscillator was used to drive both transmitters. The output of the oscillator was coupled to the grids of two separate buffer amplifiers with the buffer grid tuning condensers ganged in such a way that as one was tuned on the low side of resonance, the other was tuned on the high side of resonance. This control was used to adjust the relative phase of the driving voltage to each transmitter. The oscilloscope tuning indicators on the separate transmitter control boards placed side by side, were used to monitor the proper setting of the phase control. Improper setting would result in disorientation of the diagonal and elliptical plate patterns displayed on the scopes.

In operation, the whole system proved rather non-critical in adjustment of these operating parameters. In fact, differences in audio level of as much as one db made only slight increase in distortion at 100% modulation. Under these conditions, one transmitter would be modulated 100%, while the other was modulated one db over 100%, or approximately 110%.

The High Voltage Rectifier

Just about every transmitter manufactured today will utilize silicon rectifiers for all power supplies. Diodes are available at low cost for most any application that may confront the designer. However, there are certain precautions which must be observed in their application, especially in high power rectifiers.

The high voltage plate rectifier for each 250 kW power amplifier required an output of 18,000 volts dc at a maximum current of 27 amperes. The selection of a diode type for this job involves consideration of available short circuit current during a fault and the duration of time before primary power is removed from the faulted circuit. The limitation of available fault current is usually provided solely by the leakage reactance and resistance of the plate transformer. Although it's true that the incoming power line will have some degree of current limiting impedance, it isn't wise to depend on it. Likewise, it isn't good practice to enter things like filter choke resistance and rectifier resistance into calculation. We have found by experience that transformer impedance as high as 10 or 12% is a good compromise between supply regulation and permissible fault current for readily available diodes. 10% transformer impedance will limit fault current to 10 times normal rated current for the supply which, in our case, is 10 x 27, or 270 amperes. The additional limiting caused by line regulation, choke and rectifier resistance provides a little more safety margin.

The next step in selecting a diode is to determine the amount of time the fault current will be available, or, in other words, how quickly can the rectifier be taken off the power source? There are three basic approaches to this problem. First, vacuum relays are available which, because they draw no arc on opening, will open the circuit in about 16 milliseconds, or about one cycle of a 60 cycle power source. Second, conventional "across the line" motor starting contactors could be considered. These are considerably slower because of the arcing time of the contacts on dropout and will generally open in 2½ to 3 cycles. Third, high speed air or oil circuit breakers could be used. These are faster opening than motor starting contactors and some approach the speed of the vacuum relay. Their only disadvantages are that they are built as intricately as a Swiss watch and are therefore expensive and require more maintenance and adjustment that contactors or vacuum relays. For transmitter power up to 100 kW the vacuum relay proved to be the best choice, but for 250 kW, they become marginal in some respects so it was decided to use the 2½ to 3 cycle motor starting contactor. This was tested extensively and the collective time of opening of it, plus its signalling relay, was found to be consistently less than 3 cycles. The diode that was then selected would withstand a surge current of 340 amperes for 3 cycles, or a 270 ampere surge for 5 cycles. It carried a half wave rating of 12 amperes average current, which in the three phase full wave bridge would provide 36 amperes dc average. This is far enough above the required average current so that no forced air cooling is required. The rectifier is mounted on an open framework and cooled only by radiation and convection. A sufficient quantity of diodes were connected in series to provide a peak inverse voltage rating twice the normal operating voltage. This two to one voltage safety factor is usually applied to all semiconductor rectifier supplies.

Diodes Survive Brutal Treatment

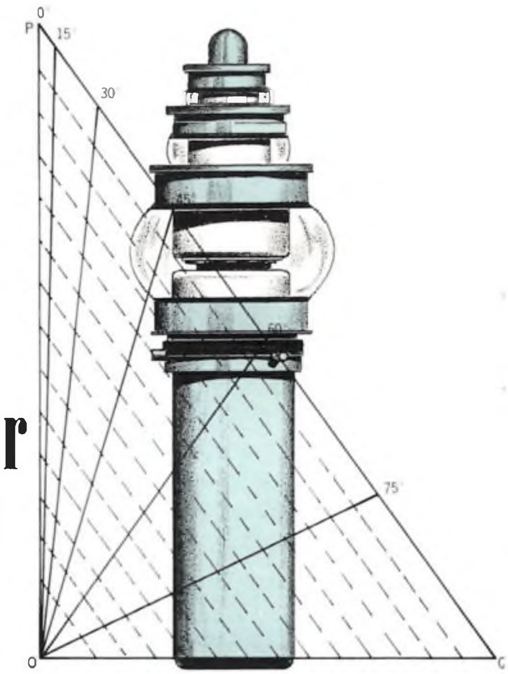
Since most of the overload operations are caused by flash-arcs in the power amplifier tubes or by arcs external to the tubes, the result is a direct short circuit on the power supply. In fact, in order to prevent damage to the fragile inner parts of the tubes during flash-arcs, the rectifier and filter condenser energy is diverted into a rectifier shorting device such as a hydrogen thyratron or ignitron tube just microseconds after the initiation of a flash-arc within a power tube. During these short circuits, the diode junction temperature rises considerably and for this reason, consideration must be given to the amount of time it takes for the junction to cool sufficiently to allow another overload if it should persist on re-applying plate voltage. This is usually one or two seconds and a time delay relay was utilized to hold off the re-closing of the plate contactor for this time.

The only other form of protection required for the rectifier is the addition of resistors and condensers across each of the seriesed diodes in order to force an equal division of the dc and ac transient and peak inverse voltage across each diode. These are usually supplied by the diode manufacturer and consist of a one or two watt 500,000 ohm resistor and a .01 to .02 mfd. disc ceramic condenser. In three months of testing, the rectifiers were shorted either deliberately or inadvertently more often than would occur in about ten years of normal operation and out of six hundred diodes used in both 18 kV rectifiers, five weak ones were lost in the first two or three days and none thereafter. When one considers the headaches endured with the old Mercury vapor rectifier, the silicon diode is indeed a boon to the transmitter designer and broadcaster.

Conclusion

In summing up the general picture of the overall transmitter design, we might add that the use of vacuum condensers which are very compact for their capacitance and voltage rating, and which require no maintenance other than an occasional swipe with a dust cloth, further enhanced the concept of a modern, highly efficient, compact and reliable transmitter. To illustrate by way of comparison its compactness, one of the two 250 kW transmitters occupies about the same floor area as some 50 kW transmitters built 25 years ago. In fact, it occupies only about twice the floor area required by some 50 kW units built today. Overall efficiency is about 66% compared to a general requirement of about 55% which is written into most specifications today, and which is what most other designs are capable of. For 250 kW this represents a power savings of about 75 kilowatts, which is almost enough to run another 50 kW Continental Electronics transmitter.

The Machlett Power Tube Calculator



Introduction

When electron tubes are used to control large amounts of power, efficiency of operation becomes of prime importance. In a power amplifier, the required high efficiency is generally achieved by permitting plate current to flow only during that portion of the operating cycle where plate voltage is low. The resulting non-sinusoidal waveforms of plate and grid current must be subjected to a Fourier Series analysis in order accurately to determine the dc, fundamental, and harmonic components of these currents which are required for the quantitative description of power tube operation.

The difficulties involved in evaluating the integrals required to determine the Fourier Series coefficients have led to the development of a number of methods of graphical harmonic analysis, by means of which these coefficients may be determined. This article describes the Machlett Power Tube Calculator, which utilizes a graphical approach based upon a combination of the methods developed by Chaffee[1] and Sarbacher[2], and which provides a good compromise between accuracy and amount of computation required.

The Machlett Power Tube Calculator consists of a transparent, graduated "Cosine Scale" overlay and a "Calculation Chart" (see attachments) which are to be used with the appropriate graph of Constant Current Characteristic curves for the tube under consideration. The transparent overlay is used to facilitate the determination of instantaneous values of the tube currents at intervals of 15° along a 90° segment of the operating line of the tube as plotted on the Constant Current Characteristic curves. Space on the Calculation Chart is provided for recording of these values, which are combined in simple arithmetic operations to yield the desired dc and peak fundamental values of the tube currents.

Use of the Machlett Power Tube Calculator

Since many readers will be familiar with similar graphical methods of Fourier analysis as applied to the operation of power amplifiers and oscillators, instructions for use of the Calculator are presented first. (These are also summarized on the overlay.) The theory behind the use of the Calculator is given in a later section for the convenience of those readers who are interested in the details.

The use of the Calculator will be illustrated by determining a set of typical operation values for the ML-6696, a general-purpose triode suitable for AM broadcasting, industrial heating, and pulse modulation, when operated as a Class C rf amplifier under conditions given in the tube data sheet for a dc plate voltage of 10,000 volts.

The following table is reproduced from the data sheet for the ML-6696:

RF Power Amplifier and Oscillator
Class C Telegraphy

Key-down conditions per tube without amplitude modulation:

Maximum Ratings, Absolute Values

DC Plate Voltage	16000	volts
DC Grid Voltage	—3200	volts
DC Plate Current	11	amps
DC Grid Current	2.0	amps
Plate Input	120	kW
Plate Dissipation	60	kW

Typical Operation

DC Plate Voltage	10000	15000	volts

— A Simplified Method for Calculating the Operating Parameters of Power Tubes

by *PETER BLOODGOOD, Associate Engineer*

DC Grid Voltage	−1200	−1600	volts
Peak RF Grid Voltage	1900	2120	volts
Peak RF Plate Voltage	8000	12500	volts
DC Plate Current	10.0	7.0	amps
DC Grid Current	0.81	0.30	amp
RF Load Resistance	440	970	ohms
Driving Power, approx.	1.5	0.60	kW
Power Output, approx.	72	80	kW

In Figure 1 will be found a graph of Constant Current Characteristics, also reproduced from the ML-6696 data sheet, which is applicable to the region of operation given in the table.

The following symbols will be used:

E_b = DC Plate Voltage

e_b = Instantaneous Value of Plate Voltage

$\check{e}_b$ = Minimum Instantaneous Value of Plate Voltage

E_p = Peak Value of RF Plate Voltage

I_b = DC Plate Current

i_b = Instantaneous Value of Plate Current

I_p = Peak Value of Fundamental Component of Plate Current

$P_{in} = E_b I_b$ = Plate Input Power

$P_o = \frac{E_p I_p}{2}$ = RF Output Power

$P_p = P_{in} - P_o$ = Plate Dissipation

$\eta = \frac{P_o}{P_{in}}$ = Efficiency

$R_L = \frac{E_p}{I_p}$ = RF Load Resistance

E_{c_1} = DC Control Grid Voltage (Bias)

e_{c_1} = Instantaneous Value of Control Grid Voltage

$\hat{e}_{c_1}$ = Maximum Positive Value of Instantaneous Control Grid Voltage

E_g = Peak Value of RF Control Grid Voltage

I_{c_1} = DC Control Grid Current

i_{c_1} = Instantaneous Value of Control Grid Current

I_g = Peak Value of Fundamental Component of Control Grid Current

$P_D = \frac{E_g I_g}{2}$ = Drive Power

$P_C = E_{C_1} I_{C_1}$ = Grid Bias Dissipation

$P_{G_1} = P_D - P_C$ = Control-Grid Dissipation

R_C = Grid-Leak Resistance

E_{c_2} = DC Screen Grid Voltage

I_{c_2} = DC Screen Grid Current

i_{c_2} = Instantaneous Value of Screen Grid Current

P_{G_2} = Screen-Grid Dissipation

In order to use the Machlett Power Tube Calculator, an operating line must first be drawn on the graph of constant current curves between the quiescent, or bias, point Q and the peak excursion point P, as shown in Figure 1. Normally, the locations of these points would be chosen tentatively by the designer on the basis of his experience with Class C amplifiers, and the calculation process carried out to determine if the resulting operation of the tube were within the desired limits. Since it is intended to check the results against those values listed in the table of typical operation, coordinates for these points appropriate to the dc plate and grid voltages, and to the peak rf plate and grid voltages listed in the table will be used. The two coordinates E_b = 10,000 volts and E_{c_1} = —1200 volts determine the quiescent, or bias, point Q on the operating line. The peak excursion point P on the operating line is reached at that moment in time when the plate voltage is minimum and the grid voltage at its positive maximum. The minimum plate voltage is equal to the difference between the dc plate voltage and the peak rf plate voltage: $\check{e}_b = 10000 - 8000 = 2000$ volts. The maximum positive grid voltage is the sum of the dc grid voltage and the peak rf grid voltage, viz., $\hat{e}_{c_1} = -1200 + 1900 = 700$ volts. The two coordinates $\check{e}_b$ = 2000 volts and $\hat{e}_{c_1}$ = 700 volts determine the peak excursion point P on the operating line, which may now be drawn connecting point P and point Q. In the half-cycle during which the instantaneous grid voltage is more negative than the bias voltage, the operating line extends an equal distance beyond point Q, but since no current can flow during this portion of the cycle, drawing this half of the operating line serves no purpose.

The Cosine Scale supplied with the Machlett Power Tube Calculator may now be used to locate the points on the operating line at which the instantaneous plate and grid currents are to be determined. Lay the transparent scale over the constant current curves in Figure 1 so that the "base lines" on the scale are parallel to the operating line drawn between P and Q on Figure 1. Keeping the "base lines" parallel to the operating line, slide the scale until sides OP and OQ on the scale pass over points P and Q respectively, on Figure 1. Before recording current values, check that these three conditions are fulfilled: side OP on the scale passes over point P on the figure, side OQ on the scale passes over point Q on the figure, and the "base lines" are parallel to the operating line. The angle lines on the Cosine Scale will now cross the operating line at points which are 15, 30, 45, etc., electrical degrees from the peak of the plate current pulse at point P. Now record on the Calculation Chart the values of instantaneous plate current i_b at these points, interpolating between the constant plate-current lines where necessary. Repeat this procedure using the constant grid-current lines to obtain the values of instantaneous grid current i_{c_1} at these points. (If the operation of a tetrode were being analyzed, it would also be necessary to record the screen grid currents at the same points. A column on the Calculation Chart is provided for this purpose.)

Calculation of the dc and fundamental components of the plate and grid currents may now be carried out as indicated on the calculation chart. The average or dc value of the plate (grid) current is found by summing the instantaneous values as shown and dividing by 12. To find the fundamental component of the plate (grid) current, each instantaneous value recorded must be multiplied by a factor which depends upon the cosine of the electrical angle at which it was measured, as indicated on the chart. The sum of these values is then divided by 12 to obtain the peak value of the fundamental component of the plate (or grid) current.

After the dc and fundamental frequency components of the plate and grid currents have been computed, the rf output power, dc input power, plate dissipation, etc., may be calculated as indicated on the chart. For example, the rf output power is equal to the product of the peak rf plate voltage (E_p = 8000 V) and the peak value of the fundamental frequency component (I_p = 18 A) of the plate current, divided by 2, or 72 kW.

It will be noted that the values of dc plate current, dc grid current, rf load resistance, driving power, and power output as calculated from the constant current curves using the above procedure agree closely with the values given under the typical operation chart. However, it must be remembered that these are *typical* operating values, and that the actual values for any given tube must be expected to vary somewhat from the calculated values.

Principle of the Machlett Power Tube Calculator

The technique employed in the Machlett Power Tube Calculator for the analysis of power tube operation is based upon two factors:

1. The existence of normal operating conditions in a tuned power amplifier. The method is strictly applicable to tuned Class B amplifiers and Class C amplifiers and oscillators, where the conduction angle of the tube is 180° or less, although good results are also obtained for Class AB_1 and AB_2 amplifiers.
2. A mathematical treatment of the non-sinusoidal currents in a power amplifier based upon a Fourier Series analysis of the current waveforms.

The plate current in a normal Class C rf amplifier flows in short pulses of less than 180° duration and is therefore not sinusoidal, but contains harmonic frequencies in addition to the fundamental frequency. However, the rf plate and rf grid voltages are sine waves (180° out of phase for a resistive load) because they appear across resonant circuits, tuned to the same frequency. A plot of grid voltage versus plate voltage for a Class C rf amplifier on mutually perpendicular axes will therefore result in an operating line that is a straight line. (Recall that two sine waves of the same frequency and 180° out of phase will produce a straight-line-trace Lissajous pattern when applied to the vertical and horizontal inputs of an oscilloscope.) Such a plot of grid voltage versus plate voltage may most readily be made on a graph of Constant Current Characteristic curves for the tube under consideration.

Figure 2 shows the result of plotting the variation in time of the grid and plate voltages in a typical Class C rf amplifier on a graph of constant current curves. The operating line is shown as extending from the quiescent, or bias, point Q, whose coordinates are (E_b, E_{c_1}) to the peak ex-

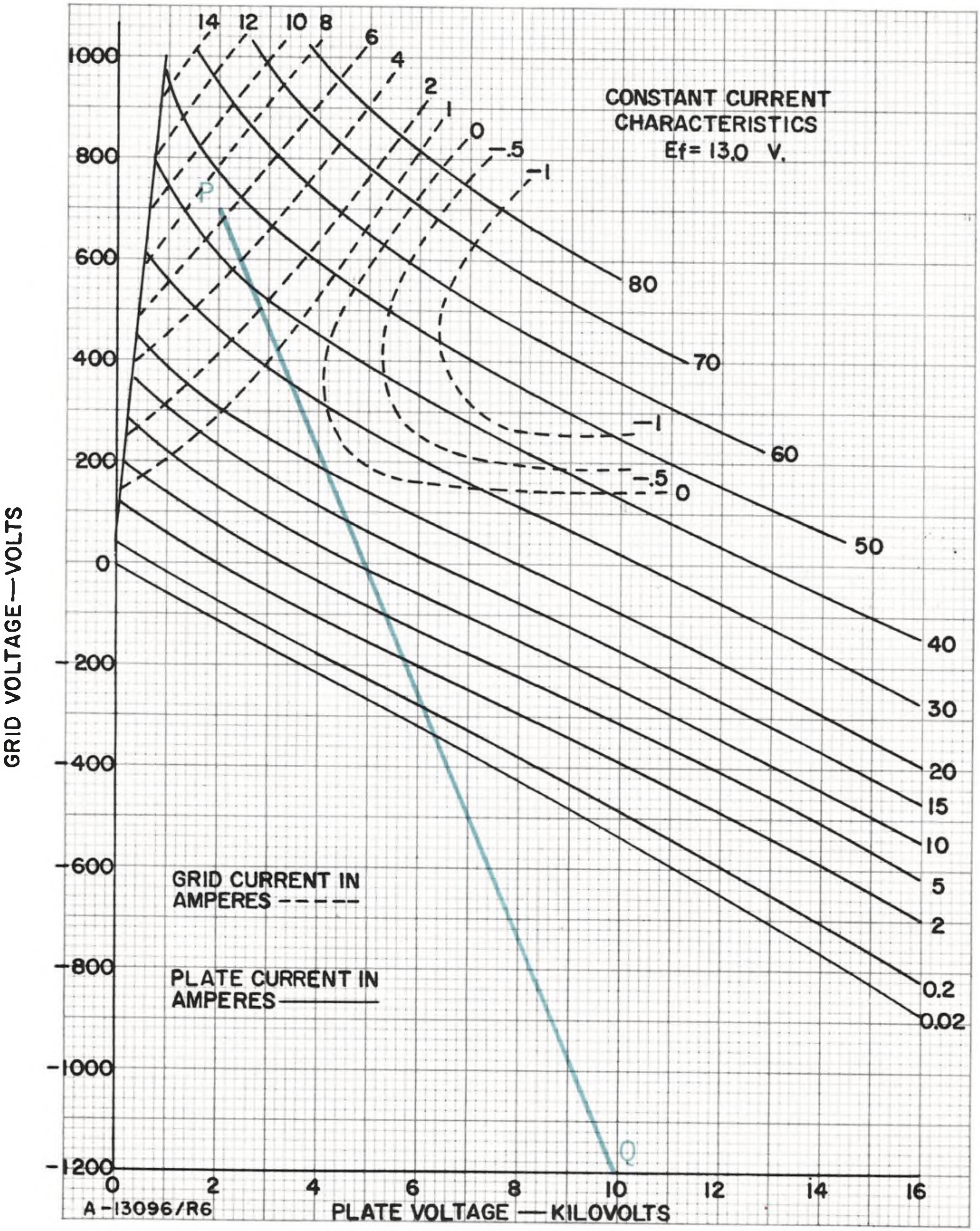


Figure 1 — Constant Current Characteristics, ML-6696 and ML-6697.

cursion point P, whose coordinates are

$$\check{e}_b = E_b - E_p,\ \hat{e}_{c_1} = E_{c_1} + E_g.$$

Beginning at $\omega t = o$, the instantaneous operating point moves along this line from point Q to Point P (at $\omega t = \pi/2$) and back to point Q at $\omega t = \pi$. The operating line actually extends an equal distance on the other side of point Q during the negative cycle of the rf grid voltage, but, since no plate or grid current can flow during this period of time, no use is made of this portion of the line.

The variation in time of the plate and grid currents resulting from this Class C mode of operation is shown in Figure 3, and is obtained by the following process. At any instant of time t, the instantaneous values of the plate and grid voltages give the coordinates of a point on the operating line on the graph of constant current characteristics. The constant plate (or grid) current line which intersects this point gives the instantaneous value of plate (or grid) current at time t. By taking a sufficient number of instantaneous current values, smooth curves such as shown in Figure 3 can be plotted. The average, or dc, content and the amplitudes of the fundamental and harmonic components of these waveforms can then be determined by a Fourier Series analysis.

The general expression for the Fourier Series expansion of a waveform f (ωt) which is a periodic function of time with period 2π is[3]:

$$f(\omega t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t),$$

where

$$a_0 = \frac{1}{\pi}\int_0^{2\pi} f(\omega t)\, d(\omega t)$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} f(\omega t) \cos n\omega t\, d(\omega t)$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} f(\omega t) \sin n\omega t\, d(\omega t).$$

For the waveforms of plate (and grid) current shown in Figure 3, which are even functions

$$i\left(\frac{\pi}{2} + \omega t'\right) = i\left(\frac{\pi}{2} - \omega t'\right)$$

where $\omega t'$ is measured from $\frac{\pi}{2}$, these terms become[3]:

$$i(\omega t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos n\, \omega t$$

$$a_0 = \frac{2}{\pi}\int_0^{\frac{\pi}{2}} i(\omega t')\, d(\omega t')$$

$$a_n = \frac{2}{\pi}\int_0^{\frac{\pi}{2}} i(\omega t') \cos n\omega t'\, d(\omega t')$$

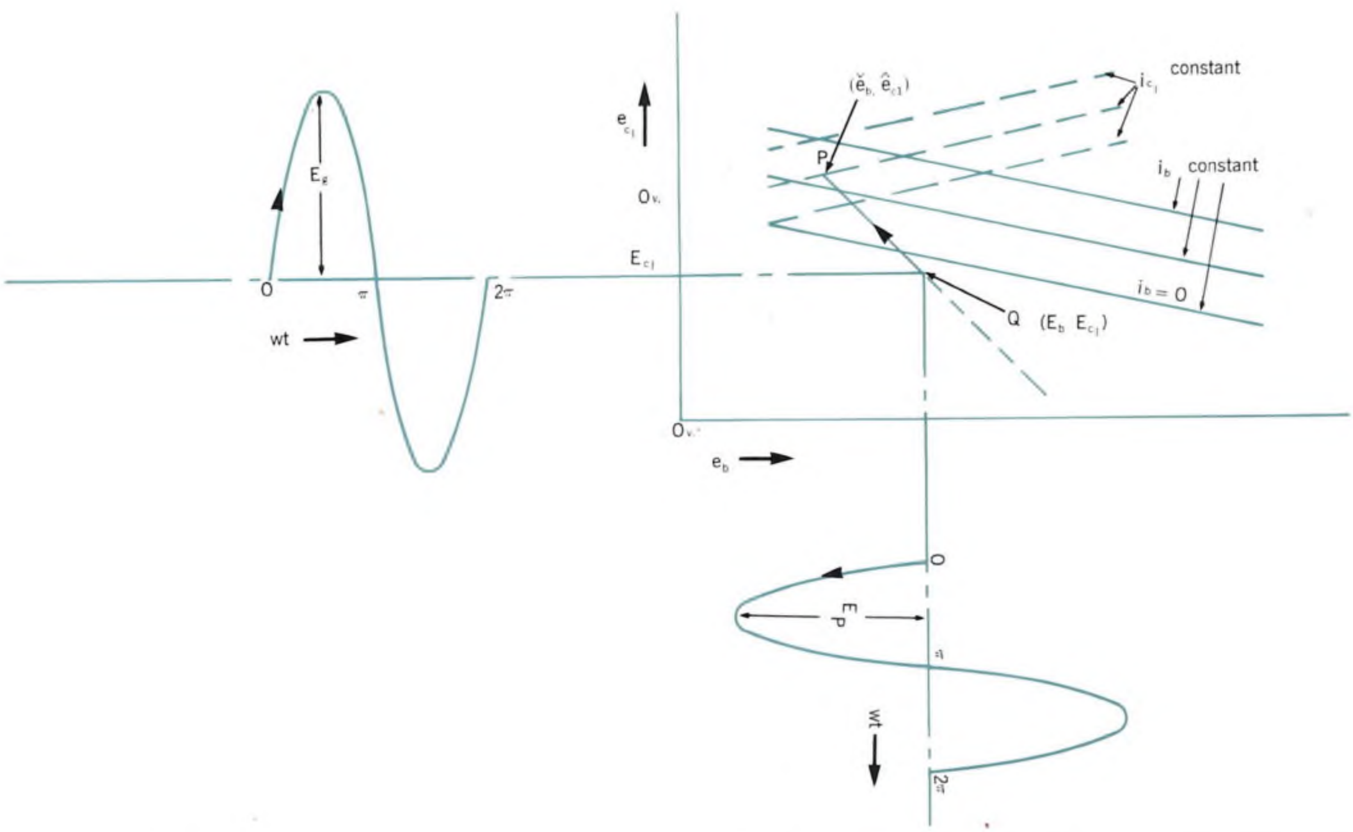


Figure 2 — Graph of Constant Current Characteristics Showing Operating Line and Sinusoidal Plate and Grid Voltages for Class C Operation.

and all b_n's are zero. The dc, or average, value of the current waveform is then $a_0/2$, the peak amplitude of the fundamental component in the current waveform is a_1, and, in general, the peak amplitude of the n^{th} harmonic component is a_n. Some difficulty will be experienced in attempting to evaluate these integrals when, as is usually the case, equal increments of grid voltage do not give equal increments of plate (or grid) current over the entire range of the load line. The resulting current waveform will not be a portion of a sine wave, and in general cannot be expressed as an explicit function of time. However, it is possible to obtain a sufficiently accurate approximation to the true values of the Fourier coefficients by substituting, for the infinite series expansion, a trigonometric series with a finite number of terms.

Let a complete cycle of the current waveform to be analyzed be divided into an even number (2m) of equal intervals of α degrees in width (see Figure 4, where m = 12 and $\alpha = 15°$). At each of the points

$$\omega t' = 0, \alpha, 2\alpha, 3\alpha, \ldots, (2m-1)\alpha$$

record the corresponding instantaneous values

$$i_0, i_1, i_2, i_3, \ldots, i_{2m-1}$$

of the current.

It can be shown[4] that the finite series expansion

$$i(\omega t') = a_0 + \sum_{k=1}^{m-1} (a_k \cos k\omega t' + b_k \sin k\omega t') + a_m \cos m\omega t'$$

assumes the values

$$i_0, i_1, i_2, i_3, \ldots, i_{2m-1}$$

at the 2m successive points in the interval from 0 to 2π if:

$$a_0 = \frac{1}{2m} \sum_{s=0}^{2m-1} i_s$$

$$a_k = \frac{1}{m} \sum_{s=0}^{2m-1} i_s \cos ks\alpha \qquad \text{for } k \neq m$$

$$a_m = \frac{1}{m} \sum_{s=0}^{2m-1} i_s \cos s\pi$$

$$b_k = \frac{1}{m} \sum_{s=0}^{2m-1} i_s \sin ks\alpha$$

for $m\alpha = \pi$.

If the origin of time is placed at the peak of the current pulse, as shown in Figure 4, $i(\omega t')$ is an even function and the sine terms will vanish. For the 15° intervals chosen here

$$\left(m = \frac{\pi}{\alpha} = \frac{\pi}{15°} \cdot \frac{180°}{\pi} = 12\right),$$

the coefficients become:

$$a_0 = \frac{1}{2 \cdot 12} [i_{0°} + 2i_{15°} + 2i_{30°} + \cdots + 2i_{75°}]$$

$$= \frac{1}{12} \left[\frac{i_{0°}}{2} + i_{15°} + i_{30°} + \cdots + i_{75°}\right]$$

if the angle of current flow does not exceed 180°.

$$a_1 = \frac{1}{12} [i_{0°} \cos 0° + 2i_{15°} \cos 15° + 2i_{30°} \cos 30° + \cdots + 2i_{75°} \cos 75°]$$

$$= \frac{1}{12} [i_{0°} + 1.93\, i_{15°} + 1.73\, i_{30°} + 1.41\, i_{45°} + i_{60°} + 0.52\, i_{75°}]$$

$$a_2 = \frac{1}{12} [i_{0°} \cos 0° + 2i_{15°} \cos 30° + 2i_{30°} \cos 60° + \cdots + 2i_{75°} \cos 150°]$$

$$= \frac{1}{12} [i_{0°} + 1.73\, i_{15°} + i_{30°} - i_{60°} - 1.73\, i_{75°}]$$

etc.

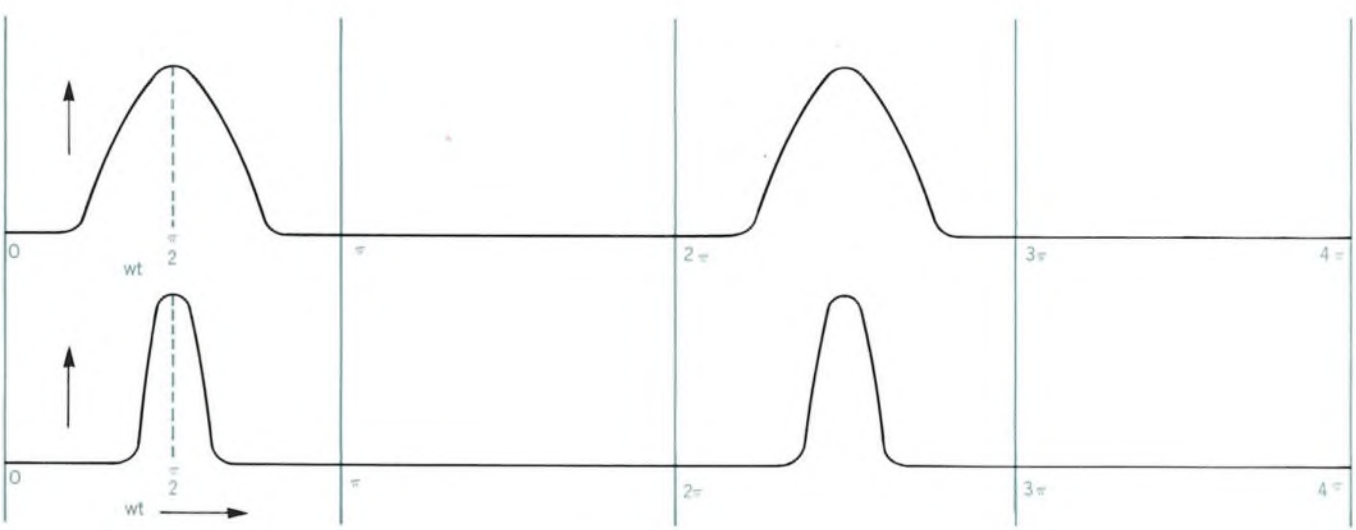


Figure 3 — Waveforms of Plate and Grid Current Drawn for Class C Operation Shown in Figure 2.

The Machlett Laboratories, Inc.

Calculation Chart for Power Tube Typical Operation

Tube Type: ML-6696 Date: ______

Class of Service: Class C RF Amplifier By: ______

Application: Illustrative use

E_b = 10000 V. E_{c_1} = −1200 V. E_{c_2} =

$\check{e}_b$ = 2000 V. $\hat{e}_{c_1}$ = + 700 V.

$E_p = E_b - \check{e}_b$ = 8000 V. $E_g = -E_{c_1} + \hat{e}_{c_1}$ = 1900 V.

P = peak excursion point ($\check{e}_b$, $\hat{e}_{c_1}$) Q = quiescent (bias) point (E_b, E_{c_1})

	Plate Current			Control Grid Current			Screen Grid Current	
P: i (0°)	46			6.8				
	23	½× / ×1	46.0	3.4	½× / ×1	6.80		½×
i (15°)	43	× 1.93	83.0	5.0	× 1.93	9.65		
i (30°)	35	× 1.73	60.6	1.4	× 1.73	2.42		
i (45°)	18	× 1.41	25.4	0	× 1.41	0		
i (60°)	1	× 1.00	1.0	0	× 1.00	0		
i (75°)	0	× 0.52	0	0	× 0.52	0		
Q: i (90°)	0	× 0	0	0	× 0	0	0	

12 | Σ = 120 12 | Σ = 216.0 12 | Σ = 9.8 12 | Σ = 18.87 12 | Σ =

I_b = 10.0 A I_p = 18.0 A I_{c_1} = 0.82 A I_g = 1.6 A I_{c_2} =

$P_o = \frac{E_p I_p}{2} = \frac{8 KV \times 18 A}{2}$ = 72 KW

$P_{in} = E_b I_b$ = 10 KV × 10 A = 100 KW

$P_p = P_{in} - P_o$ = 100 KW − 72 KW = 28 KW

$R_L = \frac{E_p}{I_p} = \frac{8 KV}{18 A}$ = 440 Ω

$\eta = \frac{P_o}{P_{in}} = \frac{72 KW}{100 KW}$ = 0.72

$\text{Gain} = \frac{P_o}{P_D} = \frac{72 KW}{1.5 KW}$ = 48

$P_D = \frac{E_g I_g}{2} = \frac{1.9 KV \times 1.6 A}{2}$ = 1.5 KW

$P_c = E_{c_1} I_{c_1}$ = 1.2 KV × 0.82 A = 980 W

$P_{G_1} = P_D - P_c$ = 1500 W − 980 W = 520 W

$R_c^* = \frac{E_{c_1}}{I_{c_1}} = \frac{1.2 KV}{0.82 A}$ = 1500 Ω

$P_{G_2} = E_{c_2} I_{c_2}$ = =

*If bias developed entirely by drop across grid-leak resistor R_c. When protective bias E_{cc} is used, $R_c = \frac{|E_{c_1}| - |E_{cc}|}{I_{c_1}}$

Note: For cathode-drive circuitry, $P_o = \frac{(E_p + E_g) I_p}{2}$, $P_D = \frac{E_g (I_g + I_p)}{2}$, $R_L = \frac{E_p + E_g}{I_p}$

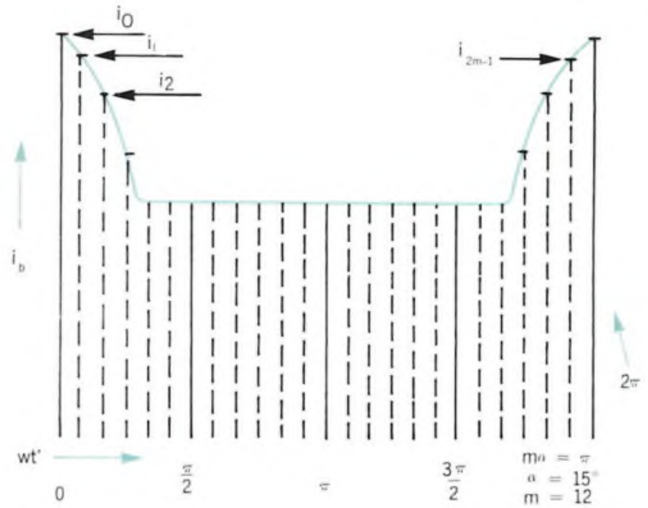


Figure 4 — Waveform of Plate Current Showing Shift in Time Axis to Make i_b ($\omega t'$) an Even Function, and Division into 15° Intervals.

The multipliers shown above are, of course, identical with those given by Chaffee for his "thirteen-point" analysis, as this latter also uses equal 15° intervals.

Since point $P(e_b = \check{e}_b, e_{c_1} = \hat{e}_{c_1})$ on the operating line is reached at the peak of the plate current pulse ($\omega t' = 0°$) and point $Q(e_b = E_b, e_{c_1} = E_{c_1})$ is reached at $\omega t' = 90°$, the operating point of the tube will move along the operating line from point P to point Q in 90 electrical degrees. If this portion of the operating line could be marked off so that the instantaneous plate and grid currents at intervals of 0°, 15°, 30°, . . . , 75° from point P could be read, the components of the current waveform could be calculated as above. The Cosine Scale supplied with the Machlett Power Tube Calculator enables this to be done. By placing the transparent scale over the graph of Constant Current Characteristics so that point P lies on the side OP and point Q lies on the side OQ of the inscribed triangle, and aligning the scale so that the "base lines" are parallel to the operating line (which, due to the geometrical properties of the triangle, insures that the radial lines intersect the operating line at the 0°, 15°, 30°, etc., points), the instantaneous plate (and grid) currents at these points in time may be recorded, and the calculation of dc, fundamental, and harmonic components carried out as above.

Criteria for Use of the Power Tube Calculator

It can be seen from the preceding discussion that two conditions must hold in order for the computations given on the Calculation Chart to be valid:

1. the waveforms of grid and plate voltage must be sine waves of the same frequency, 180° out of phase (the plate load is resistive)
2. the angle of current flow must not exceed 180° (Class B, Class C operation).

The method remains applicable even if these conditions do not hold, provided the operating line (or locus of tube operation) can be divided into equal intervals of 15 electrical degrees. The dc, fundamental, and harmonic components of the current waveforms should then be calculated by using the general expressions for the coefficients in the finite series expansion, rather than the simplified forms given on the Calculation Chart, which were derived on the basis that conditions one and two are satisfied.

This problem will arise in the analysis of the current flow in tuned Class AB_1 or AB_2 amplifiers, where it may prove desirable to include in the calculations instantaneous currents at conduction angles greater than 180°. For a sinusoidal plate voltage, operating points corresponding to any electrical angle in the cycle of operation may be located by using the fact that (refer to Figure 2):

$$e_b = E_b - E_p \cos \omega t',$$

where $\omega t'$ is measured from that instant in the cycle when point P is reached (at $\omega t' = 0$, $e_b = E_b - E_p = \check{e}_b$). Since such a point must lie on the operating line, once its horizontal coordinate is calculated as above, the position of the point is fixed. Values of instantaneous currents at these additional points, representing conduction angles greater than 180°, must now be included in the general expressions for the coefficients in the finite series expansion.

The procedure described above for locating the 15° intervals at which instantaneous currents are to be recorded is the basis for the construction of the Cosine Scale overlay. Use of this method will also prove desirable for tuned Class B and C operation in the event that the length of the operating line between P and Q is greater than the length of the longest base line on the Cosine Scale.

Conclusion

It can be seen that the Machlett Power Tube Calculator is a convenient tool for handling design problems which result from the presence of non-sinusoidal current waveforms in power amplifiers. Use of the Calculator will permit rapid and relatively accurate determination of information required for the design of a power tube stage, and will prove of particular value when the desired operating conditions for the tube are not listed in the tube data sheets.

REFERENCES

[1]Chaffee, E. L., "A Simplified Harmonic Analysis," *Rev. Sci. Instr.*, Vol. 7, pp. 384-389, October, 1936.

[2]Sarbacher, R. I., "Graphical Determination of Power Amplifier Performance," *Electronics*, December, 1942.

[3]Goldman, S., *Frequency Analysis, Modulation, and Noise*, McGraw-Hill, Ch.I, New York, 1948.

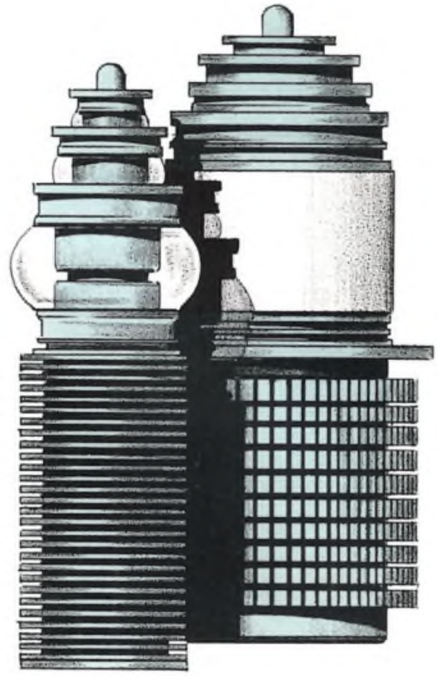
[4]Carslaw, H. S., *Introduction to the Theory of Fourier's Series and Integrals*, MacMillan, App.I, London, 1921.

[5]Mouromtseff, I. E. and Kozanowski, H. N., "Analysis of the Operation of Vacuum Tubes as Class C Amplifiers," *Proc. I.R.E.*, Vol. 23, pp. 752-778, July, 1935.

[6]Terman, F. E. and Roake, W. C., "Calculation and Design of Class C Amplifiers," *Proc. I.R.E.*, Vol. 23, pp. 620-632, April, 1936.

[7]Brown, R. H., "Harmonic-Amplifier Design," *Proc. I.R.E.*, Vol. 35, pp. 771-777, August, 1947.

[8]Chaffee, E. L., "The Operating Characteristics of Power Tubes," *Jour. Applied Physics*, Vol. 9, July, 1938.



It is the purpose of this paper to present a semi-technical discussion of this subject with a view that it be an aid in the design of liquid cooling systems for power tubes. Discussed are Heat Transfer, Turbulent and Laminar Flow, Pressure Drop, and several types of liquid coolants.

Coolants

Water

Of all the coolants used for liquid-cooled power tubes, distilled water remains the most efficient as far as heat transfer is concerned. However, the choice of coolant depends on many factors in addition to heat transfer: ambient temperature encountered in service, economics, pressure and pumping requirements, electrical isolation, system corrosion among others. On the bases of availability, economics and heat transfer efficiency, water is the most acceptable of all coolants. The principal considerations that dictate the employment of alternative liquids include the need for high voltage insulation and a broader temperature range than that possible with water. Most government and military applications impose rather severe restrictions on the ambient temperature. The ambient temperature might be as low as —20° C or as high as 80° or 90° C. Even if water can be artificially maintained by heating, the case of ambient temperatures above 80° or 90° C presents the opposite problem, which may result in temperatures well above the boiling point with resulting dangers.

In addition to these factors, the use of tap water introduces the possibility of corrosion in the presence of oxygen and a variety of metals. When water corrosivity becomes a problem, a commercial deionizer and deoxygenizer and a filter to remove corrosion particles may have to be employed.

The corrosive phenomenon is due to many factors, but the largest contributing cause in aqueous solutions is recognized as electro-galvanic action of liberated ions. In order to reduce this action, sufficient electrical insulating length must be present in the cooling pipes which connect the high voltage anode to the pump, which is usually grounded.

The resistance of the pipe or vane, R, of circular cross-section, is directly proportional to its length, L, and inversely proportional to its diameter squared, D^2. The mass, M, in grams, deposited by electro-galvanic action is equal to —

$$M = \frac{V\,t}{R\ 96{,}500}\ \frac{W}{Z}$$

where V is the voltage of the anode, R is the resistance of the vane connecting the anode to the pump, t is the time, W is atomic weight in grams, and Z is the valence. For copper W is 63.6 and Z is +2.

This formula necessarily restricts the diameter of the pipe and fixes the length so that in a time t equal to the

Electrode Coolants in Large Power Tubes

by BARRY SINGER, Research & Development Engineer

life of the tube a sufficiently small amount of copper is electro-chemically deposited.

In many systems involving high rate of water flow the diameter of the vane cannot be excessively restricted because the back pressure in a pipe increases as the diameter decreases. Hence the resistivity necessary to limit electro-chemical action must be attained by making the pipe length long enough. An estimate of the length is 1 kV/ft of water pipe. From this it is clear that a pipe may become so long that its use becomes impractical in a given system.

Oil Cooling

This insulation restriction is most important in high voltage systems and, hence, may rule out the use of water. When water is ruled out because of insulation problems, it is necessary to use an oil with better insulating properties. Common oils in use are Univolt N-35, Oranate, and fluoro-chemical liquids. In all cases the heat transfer efficiency is tremendously reduced over that of water. Univolt and Oranate are reasonably low priced high insulating oils. However, the fluoro-chemical liquids are very heavy (a specific gravity of almost 2) and very expensive (a cost of $5-$10 a pound). Although the heat transfer efficiency of these oils is very poor in comparison with water, their use is one of necessity if corrosion is also to be kept at a minimum.

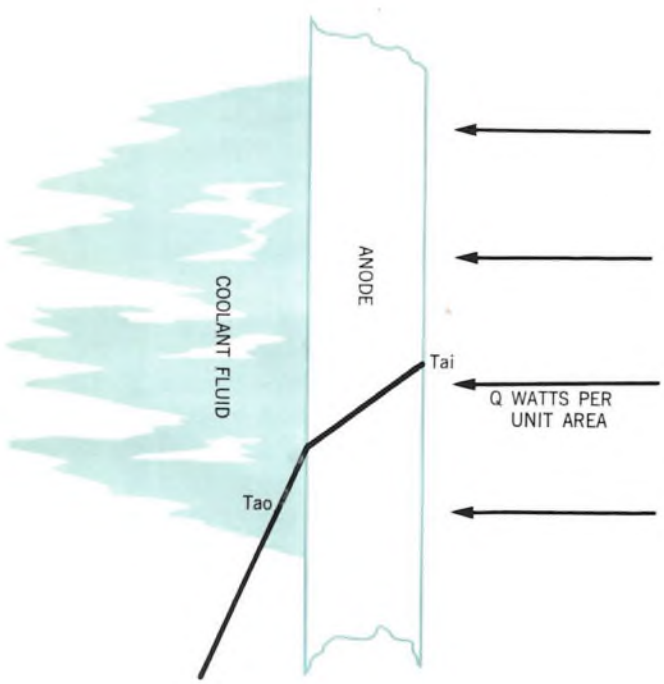


Figure 1 — Heat Transfer Process System.

Heat Transfer

General Description of Heat Transfer

In order to get a clear picture of the nature of heat transfer and to introduce the necessary parameters, a physical description of the heat transfer process will be given. Consider the system below:

Electrons strike the anode while putting Q watts per unit into the anode. The temperature drop necessary to conduct the heat flux from the inside of the anode to the outside is

$$T_{ai} - T_{ao} = .24 \frac{P\,t}{A_a K} \qquad (1)$$

where K is the conductivity of the anode material (for copper K = .9 calories per centimeter per second per degree Centigrade), and A_a is the active area of the anode in square centimeters, P is the power into the anode in watts, and t is the thickness of the anode in centimeters. Once the heat flux has reached the outside of the anode, it must be transferred into the coolant. In order to accomplish this, a thermal gradient must be set up between the anode and the coolant. The anode and that coolant which immediately touches the anode are at the same temperature. The thermal gradient must be such as to maintain a flow of Q watts per square centimeter from the outside of the anode into the coolant. The amount of flux transferred is proportional to the temperature of the anode and coolant. The constant of proportionality is the heat transfer coefficient H.

Hence —

$$H\,T_{ao} = .24 \frac{P}{A_a} \qquad (2)$$

Therefore —

$$T_{ao} = .24 \frac{P}{H\,A_a}$$

where H, the heat transfer coefficient, is in calories per square centimeter per second per degree Centigrade. T_{ao} is the outside anode temperature, which is equal to the temperature of the fluid in contact with it. The factor .24 is the conversion of watts to calories. When the anode is finned, the temperature of the anode is given by —

$$T_{ao} = .24 \frac{P}{H\,(A_a + A_f\,E)} \tag{3}$$

where P is the power into the anode in watts, A_a is the anode area, and A_f is the area of the fins in contact with the fluid. E is the effectiveness of the fin and is plotted in Figure 1 in terms of the fin length, thickness, and fluid heat transfer coefficient. The temperature rise of the fluid is given by —

$$T_{outlet} - T_{inlet} = .24 \frac{P}{C_p \rho G} \tag{4}$$

where T_{inlet} is the inlet temperature of the fluid, T_{outlet} is the outlet temperature, ρ is the density of the coolant, and C_p is the specific heat at constant pressure, and G is the flow rate in cubic centimeters per second.*

Once the inlet temperature is known, the maximum temperature of the outside of the anode can be found to be —

$$T_{anode\ max.} = T_{inlet} + \frac{.24\,P}{H\,(A_a + A_f\,E)} + \frac{.24\,P}{C_p \rho G}$$

The temperature of the inside of the anode is then

$$T_{anode\ inside} = T_{anode\ outside} + .24 \frac{P\,t}{A_a\,K}$$

From the above it will be noticed that the entire solution to the heat transfer problem rests on finding H, the heat transfer coefficient.

Description of the Heat Transfer Coefficient, H.

It should be noticed from the previous section that a knowledge of H coupled with formulae 1, 2, 3, and 4 completely determines the temperature of the system. The value of H depends to a great extent on the flow conditions of the fluid, thermal conductivity, and whether the fluid flow is turbulent or viscous. In order to determine whether the flow is viscous or turbulent, one can examine the Reynolds number. When the Reynolds number is below 2100, the flow is viscous. When the Reynolds number is above 4,000, the flow is turbulent. When the Reynolds number is between 2100 and 4,000, the flow is in a transitional region which may intermittently break into turbulence but is generally considered viscous.

In order to find the Reynolds number, RE, we use the following formula —

$$RE = \frac{D_e \rho G}{\mu} \tag{5}$$

*The following conversion may be helpful:
64 cc per second equals one gallon per minute.

The Reynolds number is dimensionless in a consistent system of units. One convenient system is as follows:

G = flow rate in cc per sec
μ = viscosity in poises
ρ = density in grams per cc^3
D_e = equivalent wetted diameter in centimeters

The quantity D_e needs some explanation. It is four times the hydraulic radius and is equal to —

$$\frac{4 \text{ x cross sectional area of flow}}{\text{Total wetted perimeter}}$$

As an example, for a circular pipe the total wetted perimeter is $2\pi R$. The cross-sectional area is πR^2. Hence the equivalent diameter is —

$$\frac{4\pi R^2}{2\pi R} = 2R = \text{Diameter of the Pipe}$$

Of course the cross-sectional area is that area normal to the flow velocity.

The heat transfer coefficient for turbulent flow, i.e., Reynolds number greater than 4,000, is given by —

$$H = .023\ (\rho)^{.8}\quad K^{.6} \left(\frac{C_p}{\mu}\right)^{.4} \frac{V^{.8}}{D_e^{.2}} \tag{6}$$

where everything has been defined previously, except for V, which is the velocity of flow which is equal to

$$\frac{\text{Flow rate G}}{\text{Cross sectional area of flow}}\ .$$

$$\text{For viscous flow, } H = \frac{N_u\,K}{D_e} \tag{7}$$

where N_u is Nusselt number and is plotted below as a function of $\frac{P_r \cdot R_e}{L/D_e}$

where P_r is the Prandtl number equal to $\frac{C_p\,\mu}{K}$

and L is the length of anode used over which heat transfer from the anode to the fluid takes place.

When the fluid is in the transitional region, i.e. Reynolds number between 2100 and 4,000, it is probably preferable to use the formula for turbulent flow when the Reynolds number is greater than 3,000; and to use the formula for viscous flow when the Reynolds number is below 3,000.

All the previous formulae which have been given are based on empirical results. In general, the formula for turbulent flow has been found to be rather accurate, while the one for laminar flow seems to give too small a heat transfer coefficient for a given set of parameters. This, however, is the best set of formulae that can be recommended. Once H is determined, we can determine the temperature of the total system from the previous section.

Turbulent Flow vs. Laminar Flow

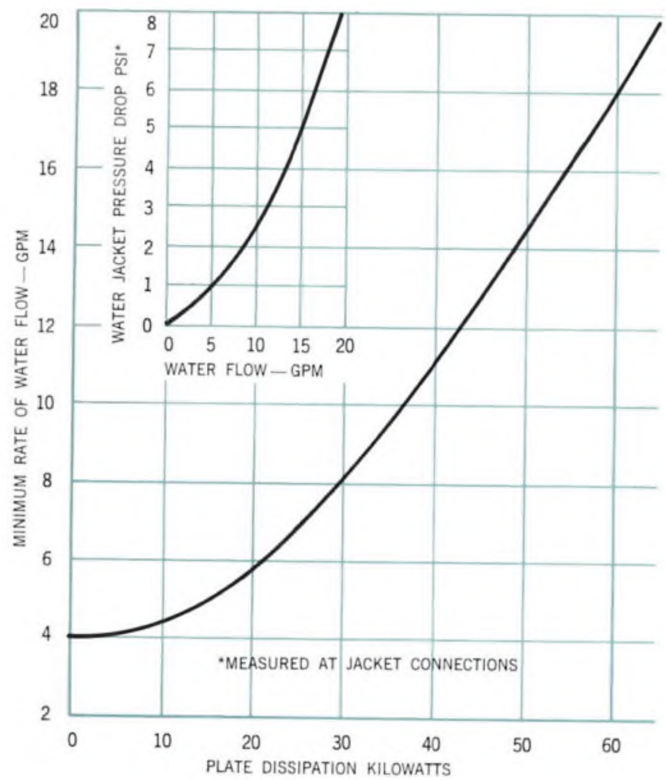


Figure 2 — Cooling Characteristics — ML-6696

It will be noticed from the above figure, which is the water-cooling curve for the ML-6696, that the minimum suggested flow rate is 4 gallons per minute. The reason for this is that at 4 gpm the fluid turns turbulent in the water jacket of the 6696. Based on a pure analysis of the temperature of the anode and fluid at 4 gpm, the temperature rise of the anode, with only filament power into the anode, is less than 10° C. The reason for suggesting the 4 gpm as a minimum flow is to be sure the fluid is turbulent.

Turbulent flow prevents the formation of vapor films between the anode and the coolant. This prevention is necessary because the films have very low heat conductivity. For example, an air film of ½ mil thickness between an oil-cooled anode and the Univolt N-35 oil will virtually triple the anode temperature at a modest flow rate, — i.e., Reynolds number greater than 250 — and for Reynolds numbers less than 100 the air film will double the temperature.

The Hazards of Laminar or Viscous Flow

In viscous flow, the water is not energetic enough to break these harmful films. As a consequence, the temperature of the anode may be from 2 to 3 times greater than the temperature calculated by using formula 7 of the previous section and the formulae of the first section. The situation grows increasingly worse once a film is formed.

In a copper anode the excess temperature caused by the film may oxidize the anode and put another film conductive barrier in the way. This vapor film may not form in the first moments of operation of the tube. A tube running with viscous flow may run well for 1000 hours, but deterioration in the next 500 hours may result in the tube's gassing up and possibly even some portion of the anode's melting.

It is for these reasons that turbulent flow is recommended whenever possible. The tube manufacturer realizes that when oils which have very high viscosity are used turbulent flow is virtually impossible. It may also be impossible when glycol and water solutions are used at low temperatures. In such cases precautions must be taken to insure the anode is running at a temperature which is very safe.

Corrosion, Turbulence and Viscous Flow

A few words are necessary concerning such things as corrosion inhibitors, oils flowing with viscous flow, and glycol-water solutions. As was mentioned in the introduction, galvanic corrosion is a problem in water systems and is a product of the free ions and oxygen in a system. The first action of the ions appears to be the build-up of a thin film at the metal surface. If oxidation film can be prevented, the surface will enjoy relative immunity to further corrosion. This is usually the role of deionizers and deoxygenizers. However this film may be detrimental to the heat transfer if the flow is not turbulent. Also, the corroded surface itself represents an impairment to heat transfer. Turbulent flow tends to wear away this corroded surface and hence maintain a relatively good heat transfer surface. There is a large life history of water used in this role, both in laminar flow with corrosion and in turbulent flow where the corrosion is constantly being worn away. However, such life data have not been obtained for oils and aqueous glycol solutions. It is known that oils tend to corrode surfaces less than water, and that aqueous glycol solutions also act as inhibitors of corrosion. Because of the sparse life data on oils and glycols, it is difficult for a tube designer to guarantee these coolants running with viscous flow for any length of time.

Discussion of Pressure Drop

No discussion of liquid cooling in power tubes would be complete without a discussion of pressure drop: i.e., that pressure necessary to maintain the flow rate through the tube. Few words can be said about this quantity, because it is virtually impossible to predict to any degree of accuracy. Only some general results can be stated. The pressure drop is proportional to the square of the flow velocity and inversely proportional to the density of the fluid. It also depends on a friction factor which is a function of the viscosity of the fluid and fluid velocity.

The back pressure of two different fluids with the same flow velocity in the same duct has been empirically found to be in the ratio of the square root of the viscosities of the fluid.

On all power tube rating charts, the back pressure is given for water cooling at various velocities. Hence, if we wish to find the back pressure for another fluid, say aqueous ethylene glycol and water solution, we would take the back pressure of the water at the desired flow velocity and multiply it by the ratio of the square root of the viscosity of the glycol to the viscosity of the water. For instance, if it were desired to know the back pressure of a 62.5 percent ethylene glycol 37.5 percent water mixture at 9 gpm in a 6696 tube, looking at Fig. 2 in the previous section, we see that for water, the back pressure is 2.4 pounds per square inch. At 65° F the viscosity of water is 1.1 x 10^{-2} poises, and the viscosity of the aqueous glycol mixture is 6 x 10^{-2} poises. Hence, at 9 gpm the back pressure for the glycol mixture in the 6696 water-jacket is —

$$2.4\left(\frac{\mu \text{ glycol}}{\mu \text{ water}}\right)^{1/2} = 2.4\left(\frac{6 \times 10^{-2}}{1.1 \times 10^{-2}}\right)^{1/2} = 5.3 \text{ psi}$$

Anything more than these extrapolations is too inaccurate to be trusted, since such unknowns as pipe roughness, construction, pressure drop, etc., would have to be known.

Summary

In designing a cooling system for high power tube operation, the most important quantity is the heat transfer coefficient. This quantity is very difficult to find. To the best current knowledge, the values for heat transfer coefficient for turbulent and laminar flow are given by formulae 6 and 7. However it must be pointed out that in the case of viscous flow this heat transfer coefficient may change in time. Parameters affecting this change are anode corrosion, oxide films formed by the surface, and local anode hot spots, etc.

All of these effects tend to deteriorate the heat transfer coefficient which in turn raises the temperature which in turn deteriorates the heat transfer coefficient more. It must also be pointed out that when inhibitors to corrosion are used, there is very little life data available, and that these inhibitors restrict the corrosion by insulating the metal anode surface by a hydroxide film, which may deteriorate the heat transfer coefficient.

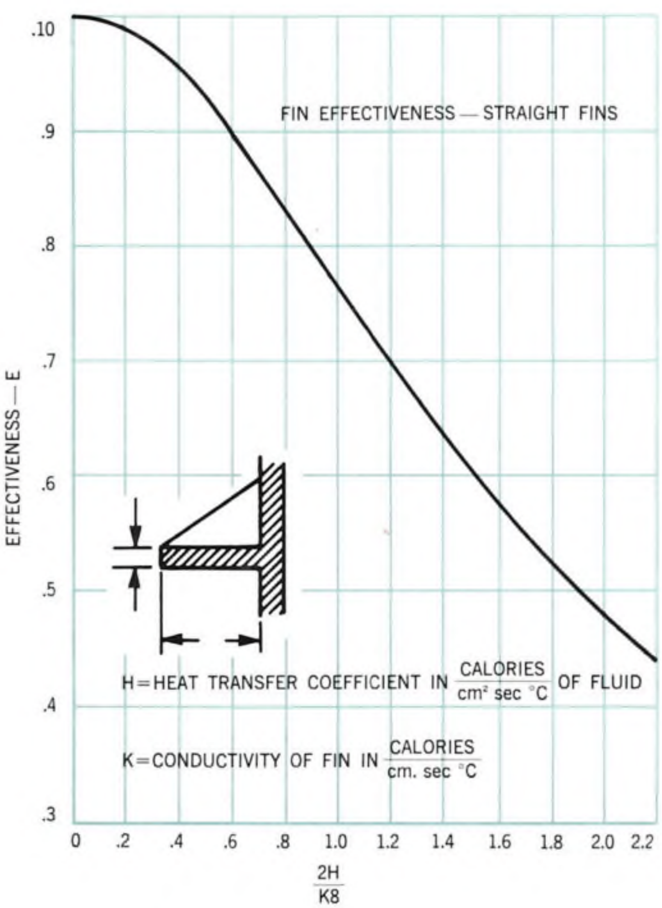


Figure 3 — Fin Effectiveness — Straight Fins

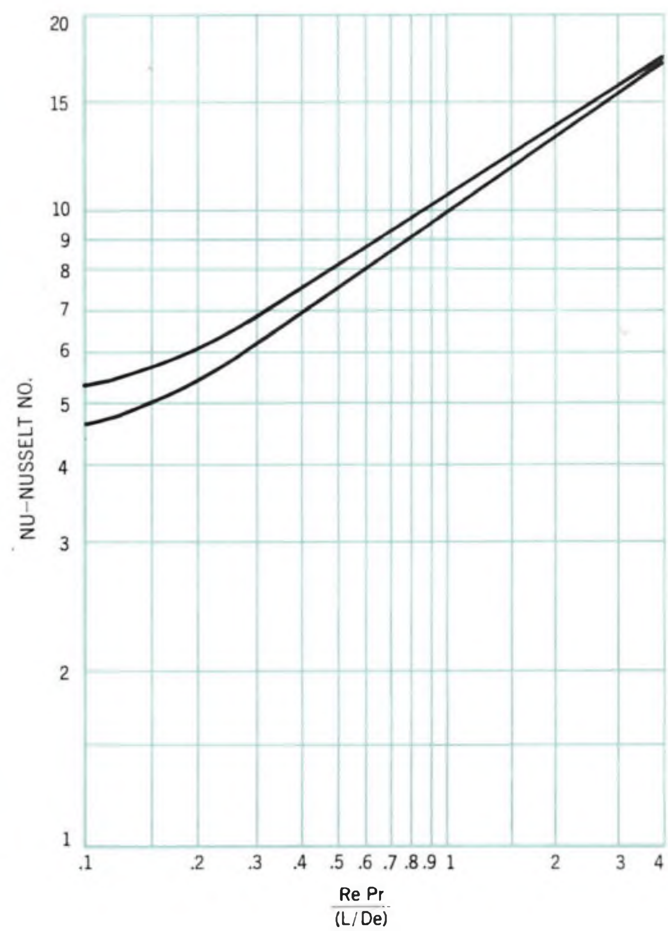


Figure 4 — Mean Nusselt Numbers Constant Temperature Difference Langhaar Velocity

Twelve Thoriated-Tungsten Type Tubes at WWV Provide Over 850,000 Hours Service

Operating for twelve, ten and nine years, respectively, at WWV, Machlett thoriated-tungsten triodes have achieved a total of over 850,000 hours without failure. Each of these twelve tubes continues in satisfactory condition.

Although the service in which these tubes operate is relatively light they have been subject to innumerable on-off cycles for regular shut-down, transmitter maintenance and so on. They have, in addition, been subject to line overvoltages such as those, for example, caused by lightning strikes.

Good maintenance and operation has been a significant factor in the tube's performance. Filament voltage (for values, see table below) is monitored to within ± 0.1 volt. It should be noted that this careful operation safely permits the reduction of filament voltage below that of the printed ratings. On shut-down, blowers are left on as filament voltage is gradually reduced; blowers remain on for 10 minutes after power is removed. All tuning is done at half power.

As pointed out in an earlier issue of CATHODE PRESS (Vol. 20, No. 3, 1963) the thoriated-tungsten tubes had, as of that date, outlasted the tungsten tubes by nearly a factor of 3 in rf service and somewhat less in the modulator units. Both these factors are now appreciably improved.

TRANSMITTER FREQUENCY	TUBE TYPE	SERIAL NUMBER	TUBE POSITION	HOURS LIFE AS OF 11-1-65	ORIGINAL INSTALLATION DATE**
5 Mc	ML-6421F	428425	RFL	71,975	5- 7-56
	ML-6421F	426798	RFR	71,975	5- 7-56
	ML-6421F	425856	ML	77,284	7-13-55
	ML-6421F	425857	MR	77,284	7-13-55
15 Mc	ML-6421F	428330	RFL	68,025	10-18-56
	ML-6421F	425611	RFR	68,025	10-18-56
	ML-5541	410244	ML	86,930	10- 9-53
	ML-5541	410108	MR	86,930	10- 9-53
10 Mc	ML-6421F	426800	RFL	70,460	4- 5-56
	ML-6421F	428328	RFR	70,460	4- 5-56
	ML-6421F	426791	ML	72,100	12-14-55
	ML-6421F	426801	MR	72,100	12-14-55

Legend: RFL — Radio Frequency, Left; RFR — Radio Frequency, Right; ML — Modulator, Left; 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 Amps. 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.

*Filaments operate within ±.1 volt.

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

EDITOR'S NOTE:

CATHODE PRESS wishes to give credit to Dr. Clifford E. Swartz for the preparation of Table 1, "Fundamental Particles and Interactions" which appeared on pages 4 and 5 of Volume 20, No. 2, 1963, in the article "The Alternating Gradient Synchrotron and Machlett Power Tubes," written by R. H. Rheaume of the Brookhaven National Laboratory. We are pleased to reprint here a revised and updated version of Table 1, together with an explanatory text. This present information is taken from Dr. Swartz's book, "The Fundamental Particles," published by Addison-Wesley Publishing Co., 1965, Reading, Mass.

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.

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} sec.

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
Inversion 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: I_3 and S

The strong (but not the electromagnetic or weak) interaction

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

The Parameters

Spin

s

In a magnetic field, a particle with spin s can exist in $(2s + 1)$ energy states.

Isotopic spin

I

Interaction with the electromagnetic field separates particles with isotopic spin I into $(2I + 1)$ 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 $Q = \overset{+}{\underset{-}{0}}$ electron charge

$$Q = e\left|I_3 + \frac{b}{2} + \frac{S}{2}\right|$$

Hypercharge

Y

Y equals twice the average charge of a multiplet.

$$Y = S + b$$

FUNDAMENTAL PARTICLES AND INTERACTIONS

CLASS	NAME	PARTICLES	ANTI-PARTICLES	REST MASS IN MEV	HALF LIFE IN SECONDS	DECAY SCHEMES
BARYONS STRONGLY INTERACTING FERMIONS (SPIN = HALF-INTEGRAL)	OMEGA HYPERON $I=0$ SPIN = $3/2\hbar$	Ω^- (S = −3)	$\bar{\Omega}^+$ (S = +3)	1676	$\sim 10^{-10}$	$\Omega^- \to \Lambda^0 + K^-$
	CASCADE HYPERON $I=1/2$ SPIN = $1/2\hbar$	Ξ^0 ($I_3=+1/2$), Ξ^- ($I_3=-1/2$) (S = −2)	$\bar{\Xi}^+$ ($I_3=+1/2$), $\bar{\Xi}^0$ ($I_3=-1/2$) (S = +2)	$\Xi^\pm \approx 1320$	$.9 \times 10^{-10}$	$\Xi^- \to \Lambda^0 + \pi^-$
				$\Xi^0 \approx 1310$	1.0×10^{-10}	$\Xi^0 \to \Lambda^0 + \pi^0$
	SIGMA HYPERON $I=1$ SPIN = $1/2\hbar$	Σ^+ ($I_3=+1$), Σ^0 ($I_3=0$), Σ^- ($I_3=-1$) (S = −1)	$\bar{\Sigma}^+$ ($I_3=+1$), $\bar{\Sigma}^0$ ($I_3=0$), $\bar{\Sigma}^-$ ($I_3=-1$) (S = +1)	≈ 1190	$.6 \times 10^{-10}$	$\Sigma^+ \to p^+ + \pi^0$ (50 %); $\Sigma^+ \to n^0 + \pi^+$ (50 %)
						$\Sigma^0 \to \Lambda^0 + \gamma$
					1.2×10^{-10}	$\Sigma^- \to n^0 + \pi^-$
	LAMBDA HYPERON $I=0$ SPIN = $1/2\hbar$	Λ^0	$\bar{\Lambda}^0$	1115	1.7×10^{-10}	$\Lambda^0 \to p^+ + \pi^-$ (67 %); $\Lambda^0 \to n^0 + \pi^0$ (33 %)
		BARYON CHARGE CENTER	ANTI-BARYON CHARGE CENTER	n 939.5	$.7 \times 10^3$	$n^0 \to p^+ + e^- + \bar{\nu}$
	NUCLEON (Proton-Neutron) $I=1/2$ SPIN = $1/2\hbar$	p^+ ($I_3=+1/2$), n^0 ($I_3=-1/2$)	$\bar{n}^0$ ($I_3=+1/2$), $\bar{p}^-$ ($I_3=-1/2$)	p 938.2	STABLE	
MESONS STRONGLY INTERACTING BOSONS (SPIN = 0)	η-MESON $I=0$	η^0		548	$< 10^{-16}$	$\eta^0 \to \pi^+ + \pi^- + \pi^0$
	K-MESON $I=1/2$	K^+ ($I_3=+1/2$), K^0 ($I_3=-1/2$) (S = +1)	$\bar{K}^0$ ($I_3=+1/2$), $\bar{K}^-$ ($I_3=-1/2$) (S = −1)	($K^- = K^+$) 494	$.8 \times 10^{-8}$	$K^+ \to \pi^0 + e^+ + \nu$ (5 %); $\to \pi^0 + \mu^+ + \nu$ (5 %); $\to \mu^+ + \nu$ (64 %); $\to \pi^+ + \pi^0$ (19 %); $\to 2\pi^+ + \pi^-$ (6 %); $\to \pi^+ + 2\pi^0$ (2 %)
		K^0, $\bar{K}^0$		K_1^0 498	0.7×10^{-10}	$K_1^0 \to \pi^+ + \pi^-$ ($\approx$34 %); $\to 2\pi^0$ ($\approx$16 %)
				K_2^0 498	4×10^{-8}	$K_2^0 \to \pi^+ + \pi^- + \pi^0$; $\to 3\pi^0$ (7 %); $\to \pi^\pm + \mu^\mp + \bar{\nu}$ (19 %); $\to \pi^\pm + e^\mp + \nu$ (24 %)
	Pi-MESON $I=1$	π^+ ($I_3=+1$), π^0 ($I_3=0$)	π^- ($I_3=-1$)	π^- 140	1.8×10^{-8}	$\pi^- \to \mu^- + \bar{\nu}$
				π^0 135	0.7×10^{-16}	$\pi^0 \to \gamma + \gamma$ ($\pi^0 \to \gamma + e^+ + e^-$ 1 %)
				π^+ 140	1.8×10^{-8}	$\pi^+ \to \mu^+ + \nu$ ($\pi^+ \to e^+ + \nu$ .01 %)
LEPTONS WEAKLY INTERACTING FERMIONS (SPIN = $1/2\hbar$)	MUON	μ^-	μ^+	105.7	1.5×10^{-6}	$\mu^- \to e^- + \nu + \bar{\nu}$
	ELECTRON	e^-	e^+ (POSITRON)	0.51	STABLE	
	NEUTRINO-MUON	ν_μ	$\bar{\nu}_\mu$	0	The neutrinos associated with $\mu^\pm$ are different from those with $e^\pm$	
	NEUTRINO-ELECTRON	ν_e	$\bar{\nu}_e$	0		
MASSLESS BOSONS (SPIN = $1\hbar$)	PHOTON	γ		0	STABLE	
(SPIN = $2\hbar$)	GRAVITON ?			0	STABLE	NOT DETECTED

SPECIFICATIONS OF MACHLETT PULSED PLANAR TYPES

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, except ML-8630, 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, ML-8537, ML-8629, ML-8630, and ML-8631.

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).

Miniature Tube Type	Conventional Tube Type	Plate Pulsed		Grid Pulsed	
		Max f	Max Power input	Max f	Max Power input
ML-8629* ML-8631*	ML-6442	5Gc+	ML-8629 and ML-8631 3000 v eb 2.8 a ib ML-6442 only 3000 v eb 2.5 a ib	5Gc+	ML-8629 only 2000 Vdc Eb 2.8 a ib ML-8631 only 3000 Vdc Eb 2.8 a ib
ML-8630	ML-6771	6Gc+	2500 v eb 1.5 a ib	6Gc+	ML-8630 only 800 Vdc Eb** 1.5 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.

*Characteristics similar to ML-6442. **Higher voltage permitted in special circuits.

NOTE: All Machlett miniature planar triodes may be soldered.

	ML-8629	ML-8630	ML-8631
Output capacitance (Cgp):	1.7 pf	1.4 pf	1.4 pf
Weight:	9 grams	9 grams	9 grams
Anode Dissipation:	100 watts	100 watts	100 watts

Send for UHF Planar Triode Brochure for data, application notes, cavity information, installation notes — over 100 pages of information.

MACHLETT
ELECTRON TUBE SPECIALIST

The Machlett Laboratories, Inc., Springdale, Connecticut, an affiliate of Raytheon Company.

Calculation Chart for Power Tube Typical Operation

Tube Type__________ Date__________

Class of Service__________ By__________

Application__________

$E_b =$ $E_{c_1} =$ $E_{c_2} =$

$\check{e}_b =$ ______ $\hat{e}_{c_1} =$ ______

$E_p = E_b - \check{e}_b =$ $E_g = -E_{c_1} + \hat{e}_{c_1} =$

P = peak excursion point ($\check{e}_b$, $\hat{e}_{c_1}$) Q = quiescent (bias) point (E_b, E_{c_1})

	Plate Current			Control Grid Current			Screen Grid Current	
P: i (0°)		½× | ×1			½× | ×1			½×
i (15°)		× 1.93			× 1.93			
i (30°)		× 1.73			× 1.73			
i (45°)		× 1.41			× 1.41			
i (60°)		× 1.00			× 1.00			
i (75°)		× 0.52			× 0.52			
Q: i (90°)	0	× 0	0	0	× 0	0	0	
	12 | Σ =		12 | Σ =	12 | Σ =		12 | Σ =	12 | Σ =	
	$I_b =$		$I_p =$	$I_{c_1} =$		$I_g =$	$I_{c_2} =$	

$P_o = \frac{E_p I_p}{2} =$ $P_D = \frac{E_g I_g}{2} =$

$P_{in} = E_b I_b =$ $P_c = E_{c_1} I_{c_1} =$

$P_p = P_{in} - P_o =$ $P_{G_1} = P_D - P_c =$

$R_L = \frac{E_p}{I_p} =$ $R_c{}^* = \frac{E_{c_1}}{I_{c_1}} =$

$\eta = \frac{P_o}{P_{in}} =$ $P_{G_2} = E_{c_2} I_{c_2} =$

$\text{Gain} = \frac{P_o}{P_D} =$

*If bias developed entirely by drop across grid-leak resistor R_c. When protective bias E_{cc} is used, $R_c = \frac{|E_{c_1}| - |E_{cc}|}{I_{c_1}}$

Note: For cathode-drive circuitry, $P_o = \frac{(E_p + E_g)I_p}{2}$, $P_D = \frac{E_g(I_g + I_p)}{2}$, $R_L = \frac{E_p + E_q}{I_p}$

THE MACHLETT LABORATORIES, INC., Springdale, Connecticut

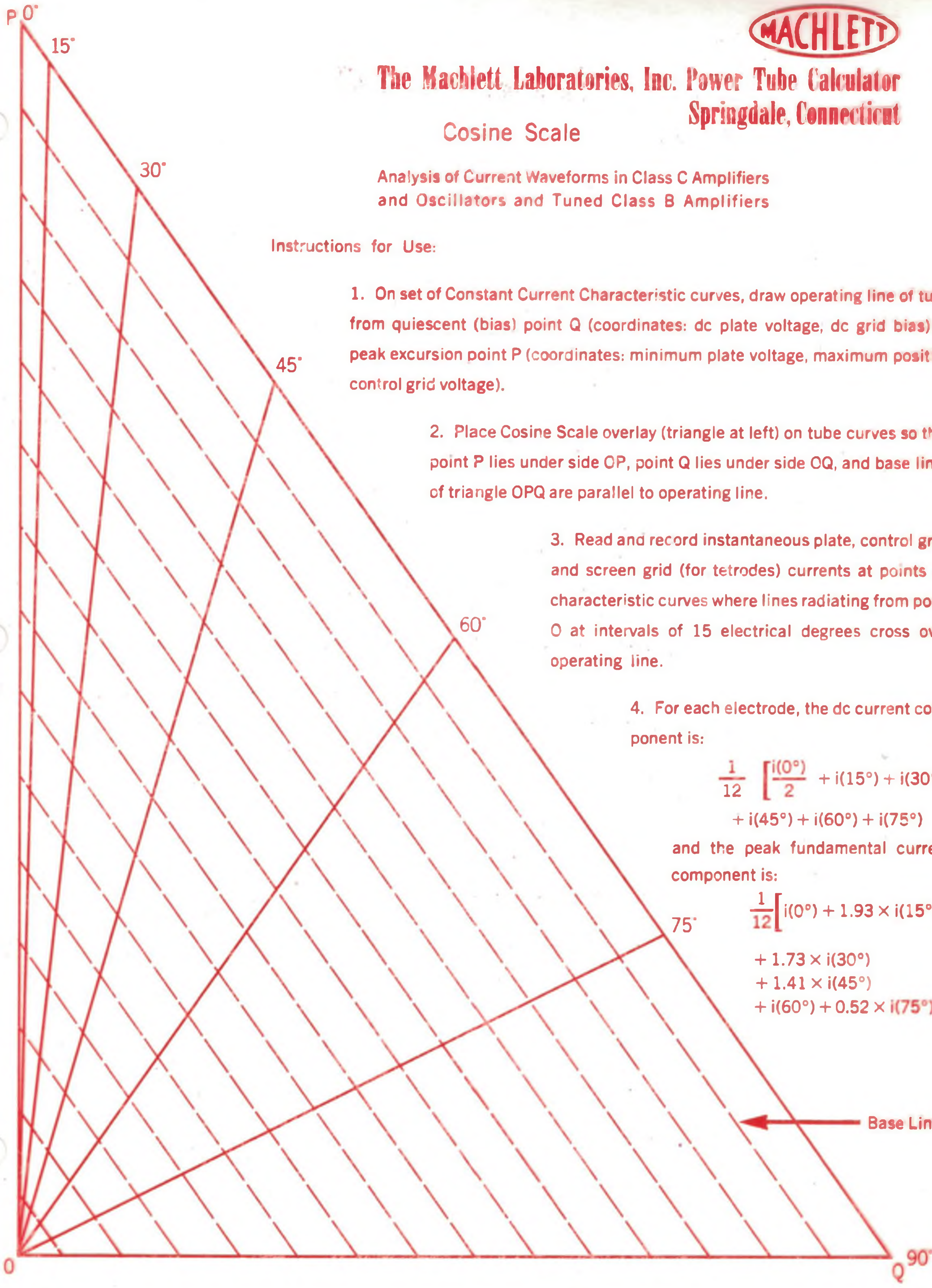
A Subsidiary of Raytheon Company

MACHLETT

The Machlett Laboratories, Inc. Power Tube Calculator
Springdale, Connecticut

Cosine Scale

Analysis of Current Waveforms in Class C Amplifiers and Oscillators and Tuned Class B Amplifiers



Instructions for Use:

1. On set of Constant Current Characteristic curves, draw operating line of tube from quiescent (bias) point Q (coordinates: dc plate voltage, dc grid bias) to peak excursion point P (coordinates: minimum plate voltage, maximum positive control grid voltage).

2. Place Cosine Scale overlay (triangle at left) on tube curves so that point P lies under side OP, point Q lies under side OQ, and base lines of triangle OPQ are parallel to operating line.

3. Read and record instantaneous plate, control grid, and screen grid (for tetrodes) currents at points on characteristic curves where lines radiating from point O at intervals of 15 electrical degrees cross over operating line.

4. For each electrode, the dc current component is:

$$\frac{1}{12}\left[\frac{i(0°)}{2} + i(15°) + i(30°) + i(45°) + i(60°) + i(75°)\right]$$

and the peak fundamental current component is:

$$\frac{1}{12}\left[i(0°) + 1.93 \times i(15°) + 1.73 \times i(30°) + 1.41 \times i(45°) + i(60°) + 0.52 \times i(75°)\right]$$