amateur service newsletter
W6SAI

modifying the Heath SB-200 amplifier for the new 8873 zero-bias triode

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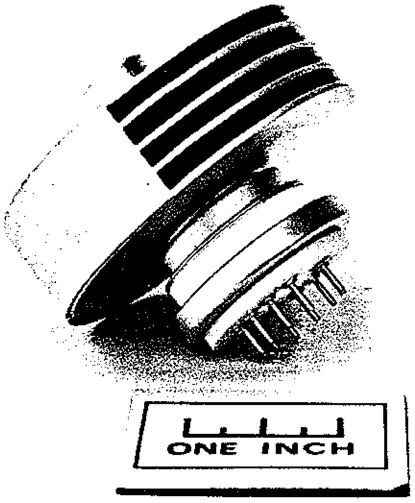
Simple modification of the SB-200 linear to provide increased power dissipation, better frequency stability, and lower drive. Two designs are featured — air cooled and conduction cooled

The high power capability, moderate cost and compact size of the new 8873 family of zero-bias, ceramic/metal power triodes make them well suited for new design, as well as for retrofit into popular amateur equipment that uses older tubes having restricted power capability and limited frequency range. The well-known Heath SB-200, a one-kilowatt PEP linear amplifier, is a likely candidate. This article covers the modification of this unit to use the new power tubes. The modification provides increased power dissipation,

The Eimac 8875 is a ceramic/metal zero-bias triode with a transverse cooler that provides 300 watts anode dissipation.



better high-frequency stability and lower drive requirements, and (in the case of the 8875) at a lower overall tube replacement cost then the original pair of tubes.

Based upon a study of the SB-200 circuit design, it was decided to try different modifications on two separate amplifiers. The first version uses the 8875, a high-mu power triode having 300 watts anode dissipation and capable of about 1200 watts peak input in Intermittent Voice Service (IVS).[1] The 8875 has five large, round, horizontal anode fins that may be adequately cooled with a small phono-motor fan, the type already in the Heath amplifier. This modification requires a minimum amount of disruption of the existing Heath circuitry.

The second amplifier has a more sophisticated and interesting modification: a conduction-cooled 8873 power triode (electrically equivalent to the 8875) is used with a finned heat sink for proper anode dissipation. The heat sink forms the vertical back wall of the rf enclosure.

This section discusses the first conversion, which provides full input level for the amplifier, with low intermodulation distortion and good tube life. The conduction-cooled version is described in the last part of the article.

the 8875 modification

The 8875 zero-bias power tube is shown in the photo and is capable of 1200 watts PEP input for ssb and 1000 watts when run in IVS service. The tube is about the size of a 4CX250B, has an 11-pin base and uses an inexpensive socket. Cathode and grid connections are brought out to multiple base pins, and, in addition, the grid is terminated in a low-inductance contact ring at the base of the tube which may be used for vhf operation. The anode is intended to be cooled by a horizontal air blast from a small fan. Dissipation is a function of cooling air, and a small phono-motor fan provides about 300 watts dissipation. For RTTY service, the power input level of the amplifier is dropped to about 600 watts. These levels are entirely compatible with the rating of the intermittent-duty power supply of the SB-200 amplifier.

The 8875 is mounted in a horizontal position in the approximate space previously occupied by the two glass tubes as shown in the chassis photo. The 11-pin tube socket is near the center of a small aluminum sub-chassis mounted to the rear wall of the amplifier enclosure. The existing cooling fan, mounted at the

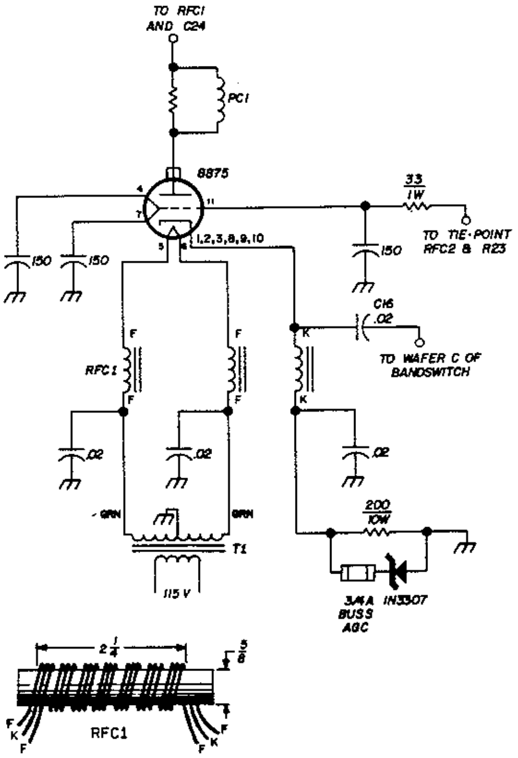


fig. 1. Revised schematic for the SB-200 shows the 8875 zero-bias triode. The 8875 requires 6.3 volts and the filament voltage in the SB-200 is on the high side because of reduced current drain. The original filament-choke windings are removed and three new windings put in their place. The filament windings are two 44" lengths of no. 20 enameled wire; the cathode winding is a 44" length of no. 26 insulated wire. Each winding has a 3" pigtail. Twenty trifilar turns are wound on the ferrite form. The ends are tied with twine and given a drop of epoxy to hold the windings in place. The socket for the 8875 is an E. F. Johnson 124-311-100. The 150-pF grid bypass capacitors are dipped mica units.

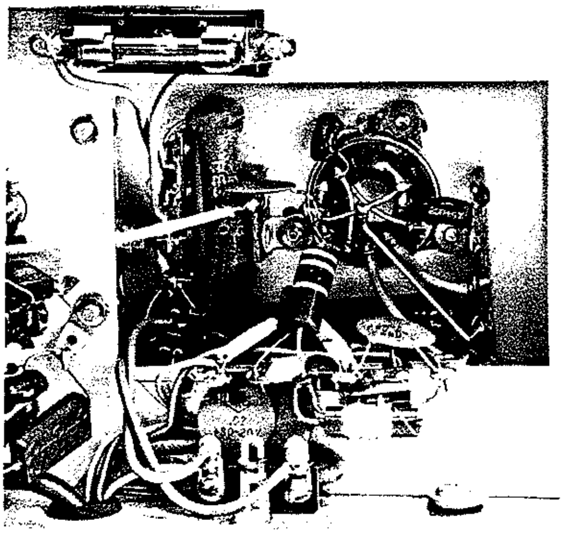
bottom of the enclosure, is moved to a new positon in respect to the anode of the 8875.

The revised circuit is shown in **fig. 1.** It uses most of the original components. A new filament choke or dropping resistor is required, as well as zener-diode bias for the 8875. All new components, with the exception of the zener fuse, are mounted within the sub-chassis, as shown in the rear-view photograph.

mechanical modifications

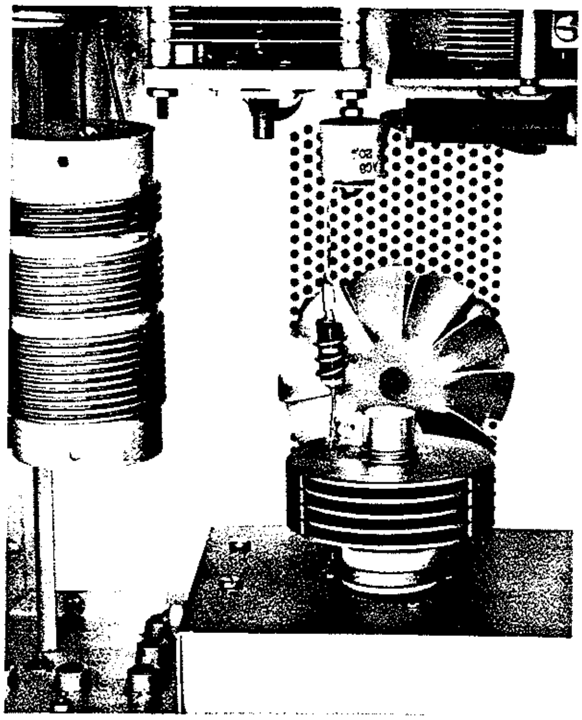
The first step is to remove the components around the existing 4-prong sockets, and then remove the sockets themselves.

Remove the filament choke from tie-point M. Unbolt tie-point AB, leaving the wiring connected. (See pictorial 11, page 39 of the Heath Instruction Manual. Original components are identified by their Heath nomenclature.) The next step is to cut out a rectangular hole on the rear wall of the enclosure as shown in the rear-view photo, with the dimensions shown in **fig. 2.** The new sub-chassis for the 8875 is placed over this hole. The sub-chassis is a 4 x 5 x 2-inch Bud AC-1404 chassis cut down to 1-¼" height and held in place with spade lugs and bolts. The tube socket is placed on the sub-chassis as shown in **fig. 2.**



The rear panel of the SB-200 is cut out to allow access to the underside of the new sub-chassis. Untouched cathode coils are to left of the cutout. The zener fuse is at top of cutout with 200-ohm cathode resistor and zener diode mounted in sub-chassis. In this installation an extra cathode choke was used with the original SB-200 filament choke. The cathode choke has 15 μH inductance and 1000 mA current rating (J. W. Miller 4624).

In the modified Heath SB-200 the 8875 is mounted horizontally in the space formerly occupied by the two glass tubes. Major plate circuit components remain unchanged.



The new sub-chassis interferes with various bolts holding the rf enclosure to the main chassis deck along the bottom rear edge, and it is necessary to provide clearance for these bolts. Proper clearance is provided by noting position of the bolts and drilling ¼-inch clearance holes in the sub-chassis at the points of interference.

Once the sub-chassis is in position, the tube is placed in the socket and the phono fan moved until the blades are positioned beneath the anode of the tube as shown in **fig. 3.**

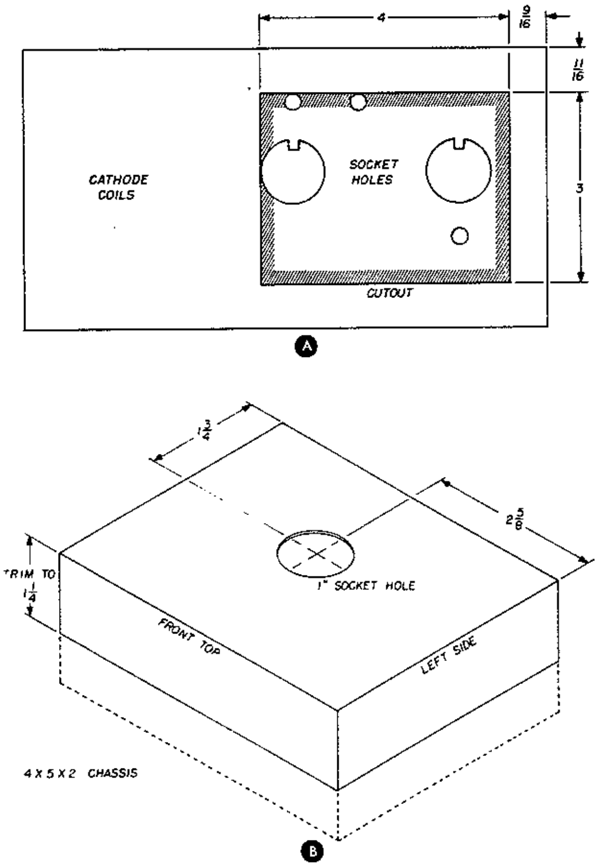


fig. 2. SB-200 chassis modifications to accomodate the 8875. The enclosure cutout for the sub-chassis is shown in A. The modified sub-chassis for the 8875 socket is shown in B.

electrical modifications

The portion of the original schematic of the SB-200 that is revised is shown in **fig. 1.** The 1N3307 8.2-volt zener diode is bolted firmly to the wall of the sub-chassis, using a thin coating of *Wakefield Thermal Compound* smeared on the zener stud to allow a good thermal bond. The new component layout in the sub-chassis is shown in the rear-view photograph.

Using the new tube, the existing filament voltage of the SB-200 is too high, and it is necessary to drop it slightly to avoid over-volting the tube filament; a 0.3-volt drop is necessary. This may be readily achieved by placing a 0.1-ohm wirewound resistor in series with one filament lead, or the filament choke may be rewound with the proper wire length and size to develop the required voltage drop. Since a cathode rf choke is required, the builder has the option of rewinding the present filament choke and adding a cathode winding as shown in **fig. 1** or using the existing choke and adding a cathode rf choke and filament dropping resistor. The latter was done for the first tests, and a new trifilar rf choke was substituted at a later date.

amplifier testing

When the modification is complete, all wiring should be checked and the resistance to ground from the anode clip should be checked. As in the original amplifier, before modification, the resistance should be about 180,000 ohms (the resistance of the filter bleeder resistor, $R_5 - R_{11}$). The amplifier should be connected to the exciter and to a dummy load. Before the amplifier is turned on, the exciter is tuned up, feeding through the unenergized antenna relay of the amplifier. The amplifier is now turned on, and the panel meter should read about +2400 volts in the HV position. Amplifier plate current is zero because of the cut-off bias voltage.

The amplifier controls are set as des-

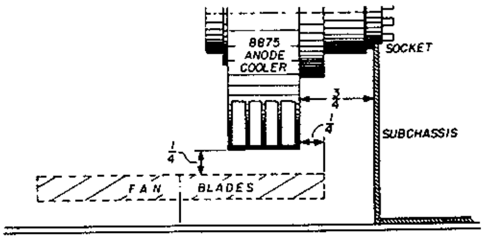
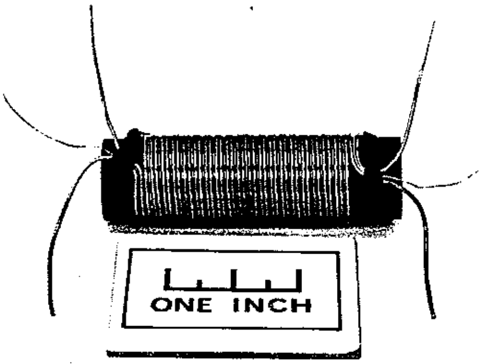


fig. 3. Phono-motor fan installation for the 8875. The motor must be moved so the shaft is in line with the center of the anode, and the tip of the fan blade clears the bottom of the tube by ¼ inch. The blade should also clear the edge of the anode by ¼ inch.

cribed in the *Operating Procedure* section of the Heath Manual (page 47), and the amplifier is again turned on. With no driver output, the meter of the amplifier should indicate an idling plate current of about 20 milliamperes. A ninety-second cathode warm up time should be observed before excitation is applied to the 8875. The drive level of the exciter is advanced until the plate current rises to about 200 milliamperes. Tuning and load controls are adjusted for maximum power output (minimum plate current) on the amplifier meter. Grid current should be about one division on the meter (25 milliamperes, or less). **Caution:** *The 8875 is easy to drive; watch out for excessive grid current.*



New trifilar filament and cathode choke for the modified SB-200 uses ferrite rod from original unit. Winding details are shown in fig. 1.

The amplifier may now be loaded for a maximum plate current of 500 milliamperes, using carrier injection from the exciter. Maximum grid current is 45 milliamperes. This corresponds to a drive level of 55 watts or less. Loading should be done quickly so as to not run excessive IVS plate current for more than 30 seconds or so.

When proper loading with carrier injection is achieved you will find that maximum power output occurs at this point along with the recommended values of plate and grid current. At maximum input the power output (measured with an accurate wattmeter) is between 520 watts (10 meters) and 630 watts (at the lower frequencies). Power gain is about 10 decibels. Under voice conditions, with no speech processing, voice peaks will run about 200 milliamperes on the meter.

Thanks to Merle Parten, K6DC, and Dick Rasor, WA6NXB, for their help and assistance in modifying the amplifier and making measurements on the completed version.

conduction-cooled linear

Modern power tubes such as the 8873-family have the capability of developing anode power dissipation densities (watts per square centimeter) comparable to the power densities in many jet and rocket engines. For this reason, effective cooling techniques are essential for long life and high tube reliability.

Conduction cooling is an efficient system of heat elimination, making use of the *heat source* (power tube or transistor), a heat transmission path (*thermal link*) and a *heat sink,* wherein the heat is removed. Many amateurs have seen transistors with tiny heat sinks on them; far fewer amateurs have observed heat-sink systems capable of dissipating several kilowatts of power. Such large systems exist, and the general design (suitably scaled down) may be adapted for use at amateur power levels. Although common in commercial and military gear, the heat-sink conduction-cooled system is just beginning to appear in amateur equipment (i. e., the Signal-One transceiver).

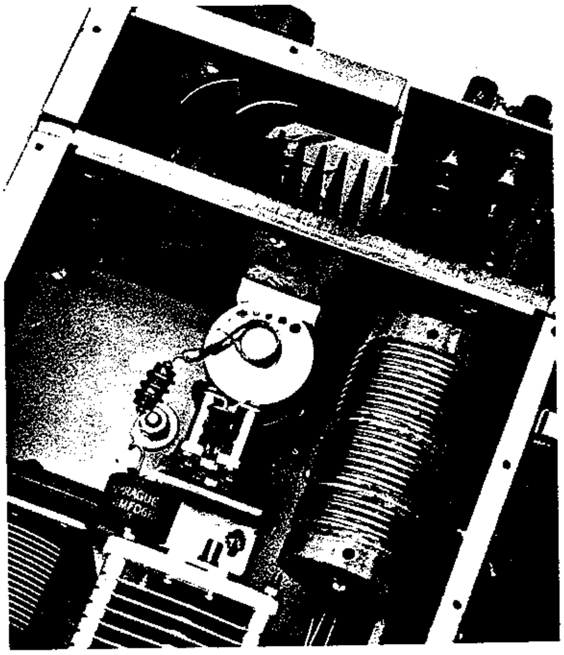
In the case of a power tube whose anode operates at a high voltage potential, the thermal link must have the dual properties of a thermal conductor and an electric insulator. One of the most practical materials for this task is *Beryllium Oxide* (BeO), an insulative ceramic (refractory) material which has the thermal conductive properties of aluminum.

The 8873 zero-bias power triode makes use of a BeO thermal link and external heat sink. The link is detachable, providing mounting flexibility and reduced tube replacement cost. However, since two thermal interfaces occur with the detachable link (tube anode to link and link to heat sink), attention must be paid to ensure low thermal resistance at these two interfaces if optimum cooling performance is to be achieved.

The heat sink, receiving heat through the thermal link from the tube anode, emits energy in the form of radiant heat. The quantity of heat radiated depends upon the absolute temperature of the sink relative to the surrounding environment and the nature of its surface. A heat sink operating at an elevated temperature compared to its environment will transfer heat to the environment by radiation, convection and conduction, as is done in this case.

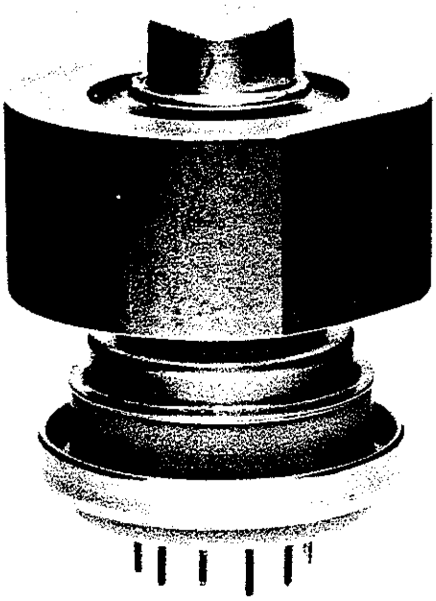
The added output capacitance of the tube supplied by the thermal link and heat sink is typically 6 to 10 pF, and this must be taken into account when vhf tank circuits are concerned.

The heat sink used with power tubes may be liquid or air cooled. In this case two or three hundred watts of anode dissipation are required so air cooling is feasible.



Conduction-cooled 8873 zero-bias triode mounted in the Heath SB-200 linear. The 8873 is held in place with a toggle clamp that presses the anode of the tube against a beryllium-oxide thermal link and finned heat sink. The flat surface of the heat sink is covered with 1/8-inch copper sheet to distribute anode heat evenly. Under normal voice operation heat-sink dissipation provides sufficient cooling. For cw or long-winded voice operation a thermal switch turns on a small phono-motor fan to hold the temperature of the heat sink at a conservative level. When heat-sink temperature drops to normal value, the fan is automatically switched off.

The 8873 conduction-cooled zero-bias triode.



the 8873

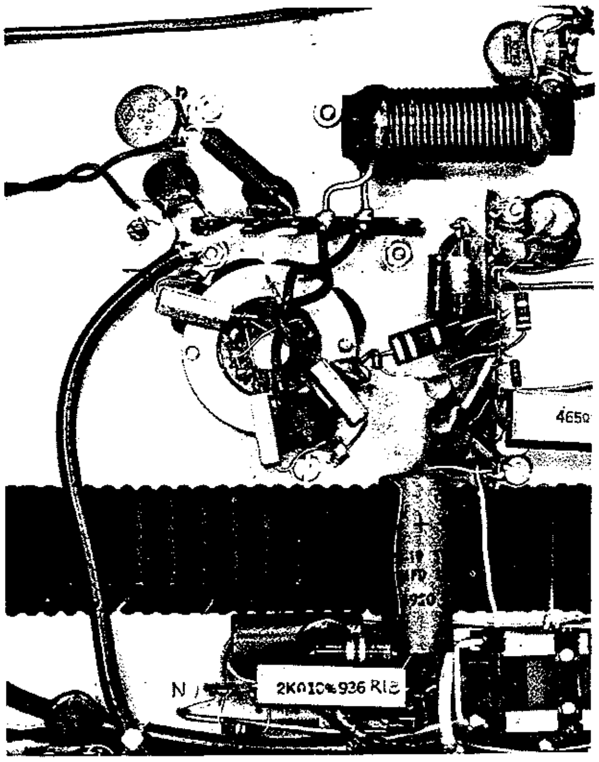
The 8873, like the 8875, is a ceramic/metal, zero-bias triode intended for hf and vhf service up to 450 MHz or so. No air cooling of the base is required if the socket is mounted on a chassis which has sufficiently low thermal resistance to drain the filament heat away from the stem of the tube.

The 8873 seemed a natural for retrofit in an existing Heath SB-200 amplifier. It was planned that the cabinet and power supply of the SB-200 could be used as a test bed for future experiments (such as a 50 MHz or 144 MHz amplifier) so a new, two-piece aluminum chassis was made. The power supply was rebuilt on one chassis and the amplifier section on another. Both units were then bolted together to resemble the original Heath chassis and shields. An amateur intending to modify his own SB-200 to this design probably would use the Heath metal work as-is.

heatsinking the SB-200 chassis

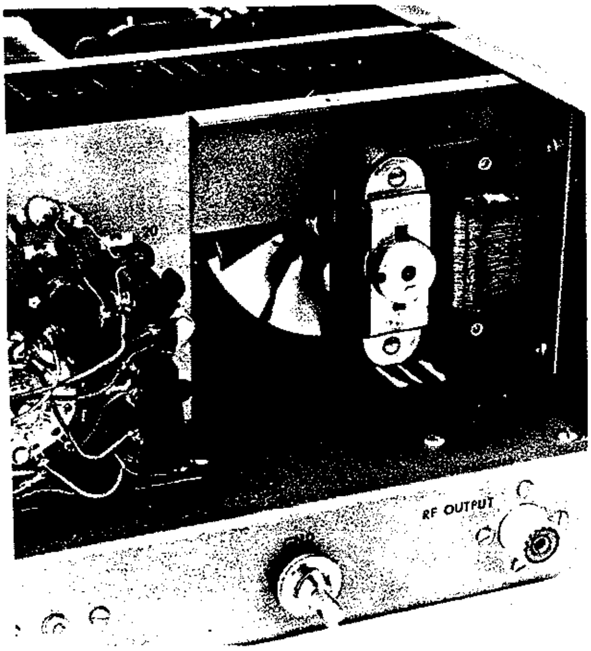
The 8873 anode is heat sunk to a finned radiator mounted at the rear of the amplifier enclosure. Generally speaking, the modification consists of removing the present tubes, sockets and auxiliary components and reworking the circuit electrically as described in the 8875 modification. Views of the heat sink installation are shown in the photographs. The heat sink measures 7-3/4 x 4-1/4 inches and is mounted to the chassis and side walls about 8-3/4 inches behind the front wall of the enclosure. The 8873 socket mounts in the center of the enclosure, with the center of the socket about 15/16-inch from the smooth surface of the heat sink.

Anode heat flows from the 8873, through a BeO insulating block into the heat sink. Good bonding is essential between these three components in order to hold anode core and seal temperatures below the maximum permitted rating of 250°C. To hold the components firmly together, a DE-STA-CO toggle clamp is mounted in front of the tube. A small ½-inch ceramic insulator is substituted for the rubber nose of the clamp, which presses against the tube and heat sink. While the clamping action takes place, the tube and socket should be free to move. Accordingly, the socket is mounted in a clamp ring so that a slight amount of rotational and lateral movement can be accomplished. The rotational movement is required in order to align the flat surfaces of the tube, thermal link and heat sink. The socket is then tightened in position after alignment and clamping takes place.



Bottom view of amplifier chassis shows submounted tube socket. Chassis bolt holes are slotted so tube and socket may be moved slightly so the anode is properly seated against the heat sink. The rear of the amplifier chassis has been cut away below the heat sink so cooling air may pass through the fins. Filament choke is at upper right with zener diode mounted on chassis at upper left.

The heat sink provides about 160 watts of continuous anode dissipation when cooled by normal currents of 20°C air (room temperature). It is possible to raise the dissipation of the sink to about 200 continuous watts by passing cooling air across it from the small phono-motor fan which was a part of the original SB-200 assembly. The fan was included in this design, along with a thermal switch.



Rear view of conduction-cooled amplifier shows cooling fan and cathode tuned circuits. Chassis beneath the heat sink has been cut away for proper flow of cooling air.

When the temperature of the heat sink approaches a value that indicates high anode temperature, the fan is automatically switched on, increasing the capacity of the sink and protecting it from long-winded rag chewers and marathon talkers.

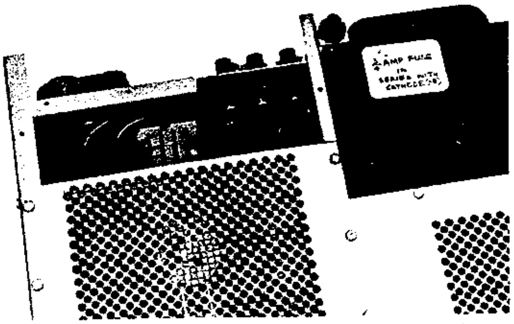
To determine the capacity of the heat sink system, temperature runs were made on the sink and tube anode, with various values of anode dissipation. Heat-sink and anode temperature were measured with temperature sensitive paint, and the thermal switch was moved about on the sink until it switched on when anode temperature reached about 180° C, well below the upper design limit of the tube.

To hold tube base temperature to a safe level, slots were cut in the chassis around the tube socket to allow cooling air from beneath the chassis to flow up and around the tube base (see under-chassis photo).

amplifier operation

Tuning and loading of the amplifier is normal, and follows the procedure outlined in the 8875 description. Under most operating conditions, the heat-sink temperature does not rise to the point at which the cooling fan is actuated, and amplifier operation is completely noiseless, a welcome "sound" these days!

While this unit is considered to be experimental, it points the way to the amplifier design of tomorrow: heat-sunk, noiseless, compact and highly efficient — quite a far cry from the old days of rack mounted gear, heavy, buzzing power supplies and black-crackle panels. How time flies!



Conduction-cooled amplifier with top shield in place. Shield has been trimmed at rear to allow air to flow over heat sink.

Again, thanks to K6DC and WA6NXB for their assistance in this experimental project.

reference

1. William I. Orr, W6SAI, "Intermittent Voice Operation of Power Tubes," *ham radio,* this issue.

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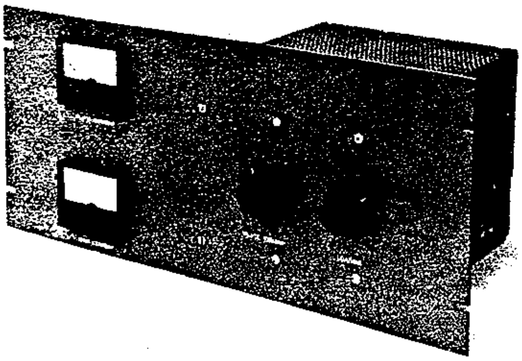


two-kilowatt linear amplifier for six meters

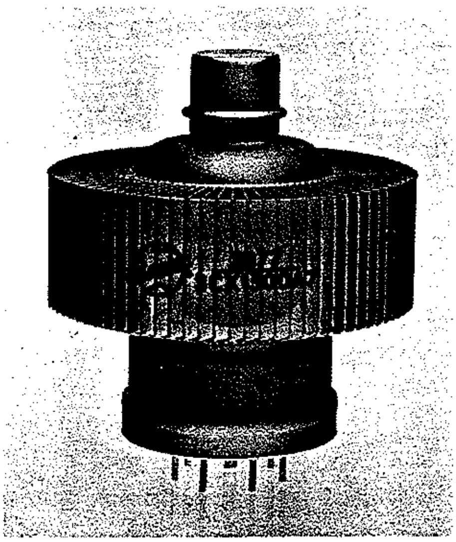
This high performance six-meter linear features the new Eimac 8877 and provides excellent stability, good reliability and minimum harmonic output

Robert I. Sutherland, W6UOV, EIMAC Division of Varian, San Carlos, California 94070

The serious six-meter operator needs a high power amplifier that will function reliably over extended periods of time and have minimum harmonic radiation. Such amplifiers seem to be commonplace for the "dc bands" but are rather rare for 50 MHz and above. Many six-meter amplifier designs are cranky, hard to neutralize or otherwise unstable or tricky to adjust.

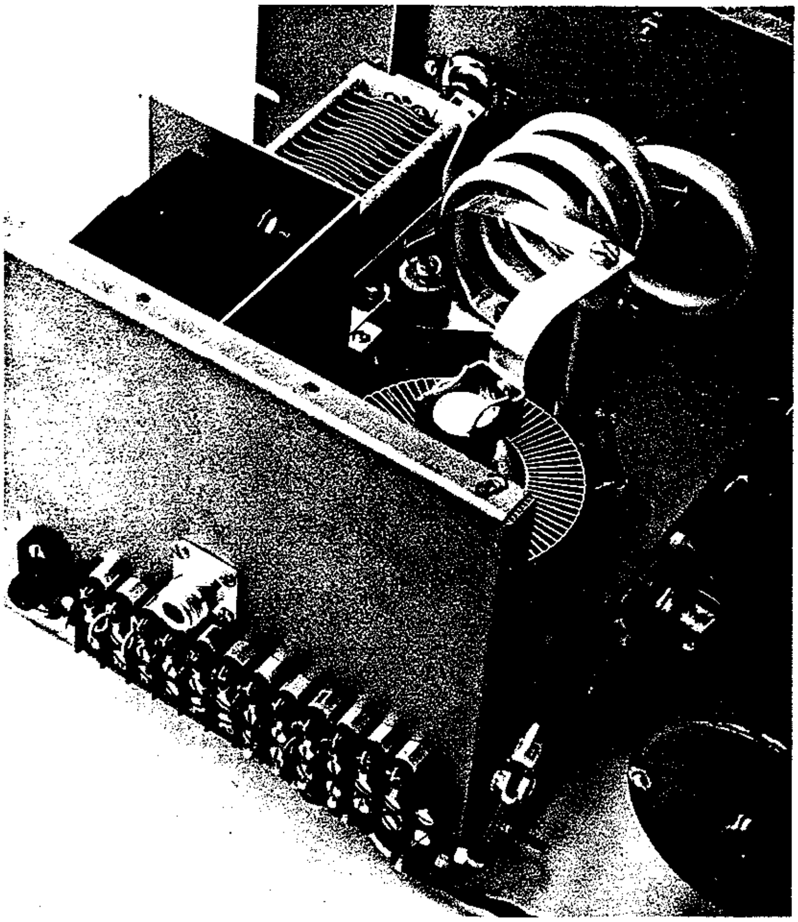
The amplifier described in this article has none of these undesirable attributes. It will run key-down on a 24-hour basis, if need be, and is stable and easy to adjust. I have used it over a period of months and it has proven to be a valuable

The new high-mu 8877/3CX1500A7 triode recently announced by EIMAC.



adjunct to the spread of six-meter equipment in my station.

This amplifier uses a grounded-grid circuit with a new high-mu triode just announced by Eimac: the 8877/3CX1500A7. This ceramic/metal triode is intended for linear service in the high-frequency and vhf range. The amplifier is intended for the maximum legal power input, 1000 watts dc, and can develop up to 2000 watts peak envelope power input during ssb operation. The amplifier requires a driver that can supply approximately 40 watts PEP at 50 MHz. Using a plate potential of 2600 volts and plate current of 750 milliamperes, power output will be about 1200 watts. This represents an amplifier efficiency of 61% and a power gain of 14.8 dB.



Top view of the plate circuit of the linear amplifier showing the shorted-turn tuning scheme. The shorted-turn is hard-soldered to shaft coupler to allow front panel tuning. The "anti-inductance" strap can be seen connecting the top of the plate choke to the plate blocking capacitor. Note that the position of the plate blocking capacitor can be changed by loosening one screw and rotating the capacitor around the screw.

A schematic of the amplifier is shown in fig. 1. The control grid is operated at dc ground with a minimum of inductance between the tube and the chassis. The plate and grid currents are measured in the cathode return lead. A 12-volt 50-watt zener diode is placed in series with the cathode return lead to set the desired idling plate current. No special neutralization scheme is needed to attain completely stable operation.

The plate circuit is a standard pi-network with tube output capacitance plus stray capacitance to the cabinet forming the input capacitance of the network (30 pF). The output loading capacitor is an air variable shunted by two fixed ceramic capacitors. Amplifier tuning is accomplished by varying the inductance of the coil by adjusting the coupling between the coil and a shorted turn.

The cathode input circuit consists of a simple T-network. The network was calculated so that a 50-ohm cable from the driver would be matched to the input impedance of the 3CX1500A7 at full power. The input impedance of the tube is 54 ohms resistance in parallel with 26 pF capacitance. The match holds over the 1-MHz tuning range of the amplifier.

A 10,000-ohm 25-watt resistor in the cathode lead of the 8877/3CX1500A7 is used to reduce standby current through the tube to a low value. When the exciter is turned on, a set of contacts on the vox relay (or other control relay) shorts out the 10,000-ohm resistor, causing the tube to operate at its normal idling plate current. The 200-ohm 10-watt resistor from the negative terminal of the plate supply to ground makes certain the nega-

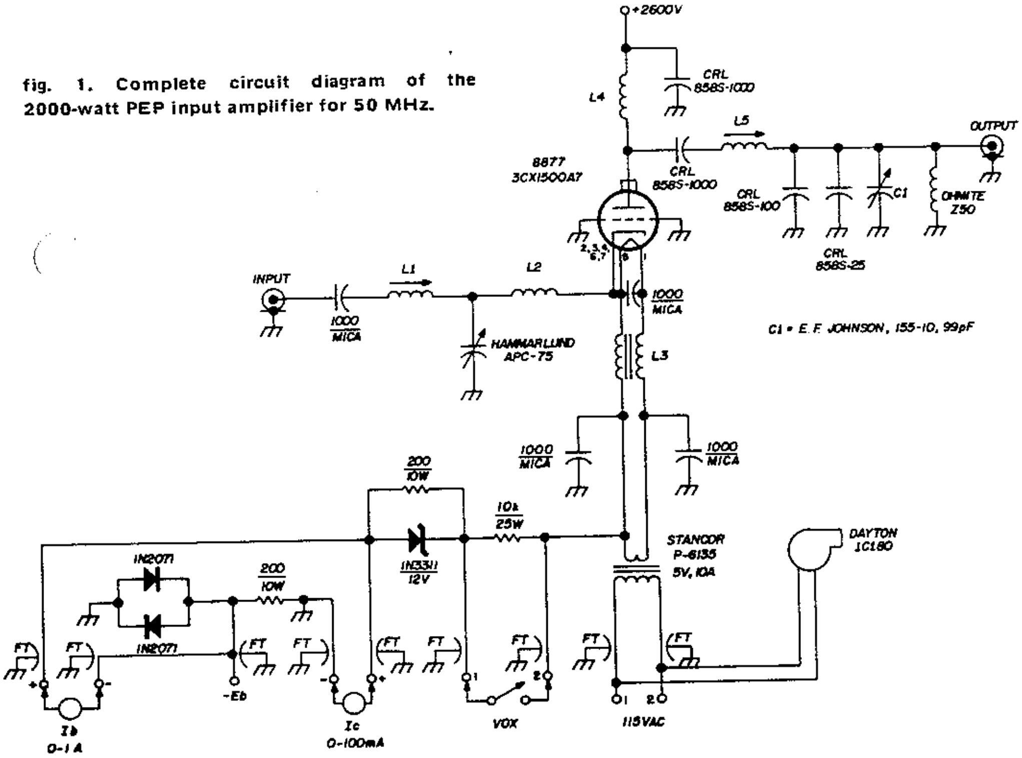


fig. 1. Complete circuit diagram of the 2000-watt PEP input amplifier for 50 MHz.

L1 6 turns no. 18 on a CTC 1538-4-3 form; coil length 7/8"

5 turns no. 18, ½" diameter, 5/8" long, elf-supporting

L3 Bifilar wound choke, ½" diameter core, 3" long, each coil 12 turns no. 10 Formvar; core is Indiana General CF-503

L4 54 turns no. 20 enameled on 1/2" diameter Teflon rod; winding length 1-13/16"

L5 3 turns 3/8" diameter copper tubing; inside diameter 1-7/8"; coil length 2-3/8"; shorted turn 2-¼" diameter 3/8" copper tubing ¼" from main coil

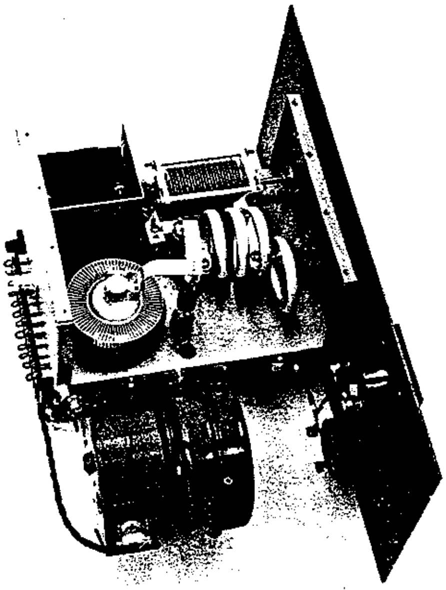
FT Erie 327 1000-pF feedthrough capacitors tive terminal does not soar to the value of the plate voltage if the positive side of the power supply is accidentally shorted to ground.

The two 1N2071 diodes across the 200-ohm resistor limit any transient surges under the shorted condition which might cause insulation breakdown. Also, these diodes afford some transient protection of the two meters by providing a path around the meters. Additional protection could be obtained by putting two back-to-front parallel connected diodes across each meter. The 200-ohm resistor around the zener provides a load for the zener and prevents the cathode voltage from becoming quite high if the zener should burn open.

the plate circuit

Top views of the amplifier chassis are shown in the photographs. The closed ring near the front panel is the shorted turn used for tuning; it is made of 3/8-inch diameter tubing, hard soldered to a brass shaft coupler with copper-silver solder. Soft solder would not be advisable in this application because of the high circulating current in the shorted turn. The "anti-inductance" strap is used to set the tank circuit to the desired tuning range. This strap runs from the top of the plate rf choke to the plate blocking capacitor. The position of the blocking capacitor can be moved to allow the strap to be flexed and set to the proper position. Note that the current through the strap is going in the opposite direction from the current in the coil at any instant and therefore causes field cancellation.

Another view of the plate circuit. The air variable across the top edge of the chassis is the adjustable part of the loading capacitor. Two ceramic barrel capacitors are mounted in parallel with the air capacitor and can be seen at the end of the variable capacitor near the filament transformer shield.



To set the amplifier to the low-frequency end of the band, the shorted turn is completely decoupled and the position of the blocking capacitor and the anode strap adjusted to resonate the plate circuit to 50 MHz. As the shorted turn is coupled tighter, the total inductance in the plate tank circuit will be reduced, causing the resonant frequency to increase. When the shorted turn is fully coupled, the resonant frequency of the plate tank circuit will be about 51 MHz.

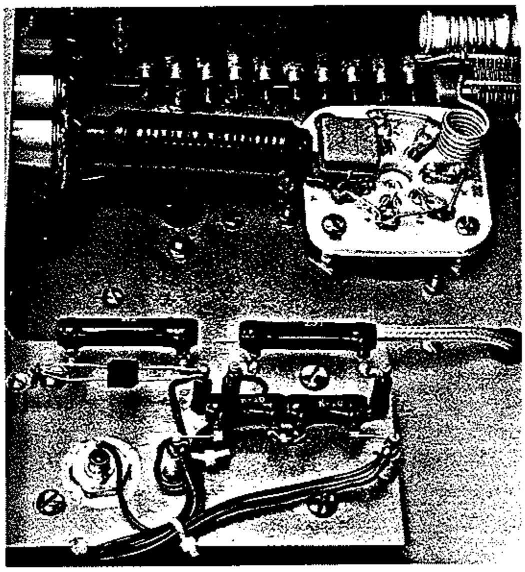
Amplifier loading is accomplished in the same manner as in a typical pi-network amplifier. The loading capacitor is the air variable along the top right edge of the chassis. The two ceramic fixed capacitors are at the left end of the air capacitor and at the end of the coaxial cable coming from the type-N coaxial receptacle mounted on the back panel.

The plate choke is made of 54 turns of no. 20 enameled wire closewound on a one-half inch diameter Teflon rod. The winding length of the coil is 1-13/16 inches. The choke is mounted on top of the ceramic capacitor which is used to by-pass the B-plus end of the choke.

Visible on the back of the front panel are the *Jackson* ball-drive assemblies. These handy devices provide a very smooth and slow "feel" to the tuning. The 5.0-volt 12-ampere filament transformer is visible inside its aluminum shield at the top left end of the chassis.

the input circuit

The input matching network is a standard T-design consisting of two series coils and one shunt capacitor. One coil and the shunt capacitor are variable. With these two adjustments it is possible to cover a wide range of impedance transformations. The controls for the variable elements are brought out the left rear side of the chassis. Once the adjustments have been made, no tuning is required over the first megahertz of the band.



View of the underside of the chassis showing the input circuit and the location of the zener diode and resistors. The T matching network is in the upper right hand side of the chassis. The heater-cathode choke is mounted between the socket and the ceramic stand-offs at the left side of the picture. Note that the socket is mounted below the chassis to allow passage of the cooling air. The straps grounding the grid to the chassis can also be seen under the threaded brass spacers used to sub-mount the socket.

The input matching network can be seen in the top right corner of the under chassis photograph. The cathode-heater rf choke is near the tube socket. The choke is bifilar wound with twelve turns on each coil using no. 10 Formvar insulated wire. The core material is *Indiana General CF-503,* one-half inch in diameter.* The core permeability is a little high for this application, but the material was available and has not given any trouble. The Johnson 122-247-202 socket is mounted one-half inch below the chassis using threaded brass spacers. Four pieces of brass shim stock, or beryllium copper, are formed into an "L" shape to mount between the brass spacers and the chassis and make contact to the control grid ring.

the tube

The 8877/3CX1500A7 is a new ceramic triode having good division between the plate current and the grid current. It has EIA base no. E7-2 which can be used with the standard septar sockets. The tube has a plate dissipation rating of 1500 watts, and has a mu of approximately 200. The cathode is indirectly heated, and the filament requirements are 5.0 volts at 10 amperes.

performance data

Many different operating conditions were tried with this amplifier. The conditions most suitable for amateur ssb operation at 2000 watts PEP input are:

Plate voltage	2600 Vdc
Plate current (single-tone)	750 mA
Plate current (idling)	40 mA
Grid voltages	-12 Vdc
Grid current (single-tone)	58 mA
Power input	1950 W
Power output	1200 W
Efficiency (apparent)	61 %
Drive power	40 W
Power gain	14.8 dB

The intermodulation distortion products at full peak envelope power input under the above operating conditions are:

3rd order	-44 dB
5th order	-37 dB
7th order	-64 dB
9th order	-68 dB

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*Available from Newark Electronics Corporation, 500 North Pulaski Road, Chicago, Illinois 60624. Order catalog number 59F1521.

amateur service newsletter
W6SAI

rating tubes
for linear amplifier service

Peak envelope power
and
intermodulation
distortion
are important parameters
when selecting tubes
for linear amplifiers —
here's what they mean
and how they are measured

Robert I. Sutherland, W6UOV, William I. Orr, W6SAI, Eimac division of Varian

The power-handling capability of a given tube in single-sideband service depends upon the nature of the signal being transmitted and the tube's power dissipating capability. The method of establishing single-sideband service ratings should be such that relatively simple test equipment can be used to determine whether or not a tube is operating within its maximum ratings.

It is impractical to establish a rating based on voice-signal modulation because of the irregular waveforms and the varying ratios of peak-to-average signal power found in different voices. The most convenient rating method, and probably most practical, uses a single-tone audio signal to modulate the ssb transmitter. By using this test signal at its full modulation capability, the amplifier will operate under steady, maximum-signal conditions which are easily duplicated and observed.

When a single sine-wave tone modulates a single-sideband transmitter the rf output appears as a steady, unmodulated signal on an oscilloscope (see **fig. 1A**). This is because the output is a continuous signal having a frequency removed from that of the carrier by the modulating frequency, as shown in **fig. 1B**.

two-tone tests

Consequently, the operation of a linear amplifier under single-tone modulation is comparable to that of a cw transmitter under key-down conditions. As such, the performance of the power-amplifier stage at maximum signal (or peak) conditions can be determined from meter readings. However, this simple test lacks information on the linearity of the

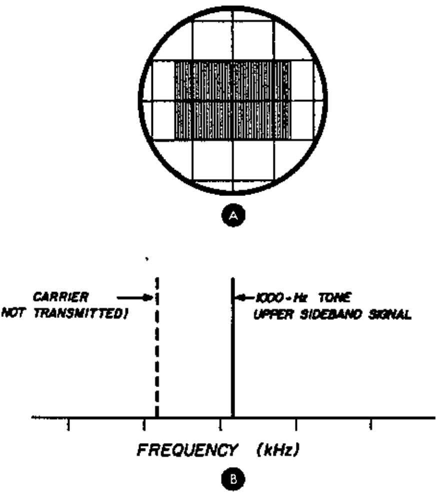
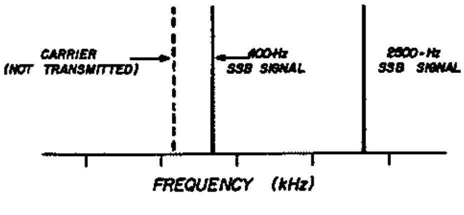


fig. 1. Rf output of ssb transmitter with single-tone modulation. Oscilloscope pattern is shown in A; spectrum is shown in B.

stage. To study linearity by observing amplifier output, some means must be provided to vary the output signal level from zero to maximum with a regular pattern that can be easily interpreted. A simple means is to use two equal-amplitude audio tones to modulate the ssb transmitter. This is termed a *two-tone* test. With this procedure the transmitter emits two steady signals separated by the frequency difference of the audio tones (**fig. 2**).

In some ssb generators, the two-tone signal is obtained by impressing a single tone at the audio input and injecting the carrier (by unbalancing the balanced modulator) to provide the second equal amplitude rf signal (**fig. 3**). The resultant beat between the two rf signals produces a scope pattern which has the appearance of a carrier 100 per cent amplitude-modulated by a series of half sine waves as shown in **fig. 4.**

fig. 2. Spectrum of ssb transmitter modulated by a two-tone test signal containing 400- and 2500-Hz tones and transmitting upper sideband.



When using the two-tone technique to measure the distortion of a linear rf amplifier it is sometimes more expedient to use two rf signal sources (separated in frequency by the desired number of cycles) and to combine them in a manner which will minimize the interaction between them. The two rf signals represent the two equivalent sideband frequencies generated by the two-audio-tone system and produce exactly the same scope pattern.

A linear amplifier is usually rated at peak envelope input or output power level. *Peak envelope power* (PEP) is the root-mean-square (rms) power generated at the peak of the modulation envelope. With two-tone or single-tone test signals the approximate relationships between single-and two-tone meter readings, peak envelope power and average power (class B or AB operation) can be determined from the formulas shown in **appendix 1.** Although the equations for average power output are different for the two tests, the PEP formulas are identical.

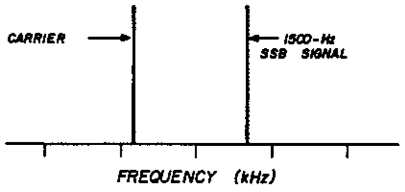


fig. 3. Spectrum of ssb transmitter modulated by 1500-Hz tone and injecting carrier to obtain second rf signal equal in amplitude to the tone.

multitone relationships

The approximate equations given in **appendix 1** are for single- and two-tone conditions, the most common test situations. However, in some multi-channel transmitter applications many more tones are used. The following method can be used to determine the peak-envelope-power to average-power ratio. (For the purposes of this explanation it is assumed that all the tones are equal.)

The following examples demonstrate two important relationships between single and multitone signals amplified by a linear system.

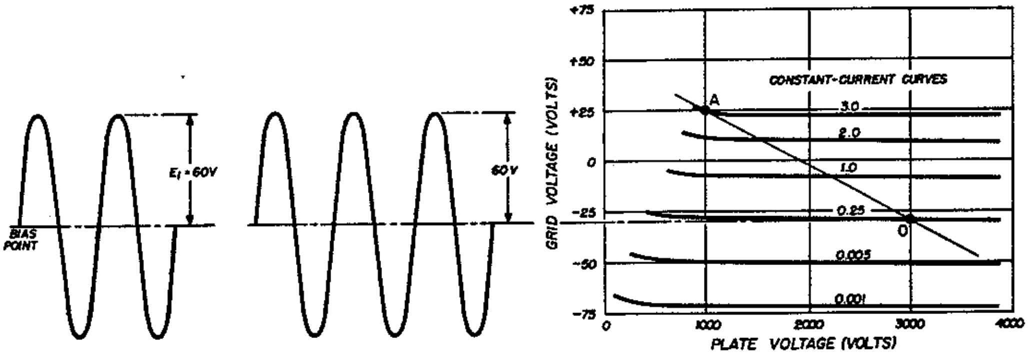


fig. 5. Single-tone condition.

Assume the amplifier is set up for a single-tone driving signal and a Point "A" on the operating line is established (see fig. 5). A definite PEP output is developed under this condition. To drive this linear amplifier to the same PEP output with a multitone signal, the drive signal voltage for each tone must be 1/nth (n = number of tones) the amplitude of the single-tone signal.

By assuming a perfectly linear amplifier where the input waveshape is exactly reproduced in the output load, these grid waveshapes can be used to demonstrate the relationship of PEP to Average Power.

For the single-tone case, PEP = Average Power; for the two-tone case, PEP = twice Average Power. However, in the two-tone case the average power is one-half that of the single-tone case, so the resultant peak envelope power ratings are identical.*

The two test frequencies (f_1 and f_2) are equal in amplitude but slightly different in frequency. As a result, when they are exactly in phase the two crest voltages add directly to produce the crest of the two-tone envelope. When the two frequencies are exactly out of phase the

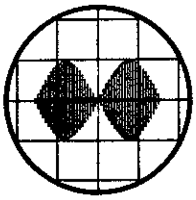


fig. 4. Scope pattern of ssb transmitter modulated by two-tone test signal.

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*This is best illustrated with two practical examples.

single-tone

$$\text{Average power} = \frac{E_1(\text{rms})^2}{R_L} = \frac{\left(\frac{60}{\sqrt{2}}\right)^2}{R_L} = \frac{1800}{R_L}\ \text{W}$$

$$\text{PEP} = \frac{E_1(\text{rms})^2}{R_L} = \frac{\left(\frac{60}{\sqrt{2}}\right)^2}{R_L} = \frac{1800}{R_L}\ \text{W}$$

Therefore, PEP = average power

two-tone:

$$\text{Average power} = P_{1avg} + P_{2avg} = \frac{E_1(\text{rms})^2}{R_L} + \frac{E_2(\text{rms})^2}{R_L}$$

$$= \frac{\left(\frac{30}{\sqrt{2}}\right)^2}{R_L} + \frac{\left(\frac{30}{\sqrt{2}}\right)^2}{R_L} = \frac{450}{R_L} + \frac{450}{R_L} = \frac{900}{R_L}\ \text{W}$$

$$\text{PEP} = \frac{(E_{1rms} + E_{2rms})^2}{R_L} = \frac{\left(\frac{30}{\sqrt{2}} + \frac{30}{\sqrt{2}}\right)^2}{R_L}$$

$$= \frac{\left(\frac{60}{\sqrt{2}}\right)^2}{R_L} = \frac{1800}{R_L}\ \text{W}$$

Therefore, PEP = 2 × P_{avg}

cusp of the two-tone envelope results (see **fig. 6**).

Note that the voltage amplitude at the crest of the resultant two-tone envelope is equal to that of the single-tone envelope and therefore the tube is driven to the same point on the operating line in each case. If the tube is driven to the same peak plate current and the same peak plate voltage swing by different excitation signals, then the peak envelope power output for both signals is the same.

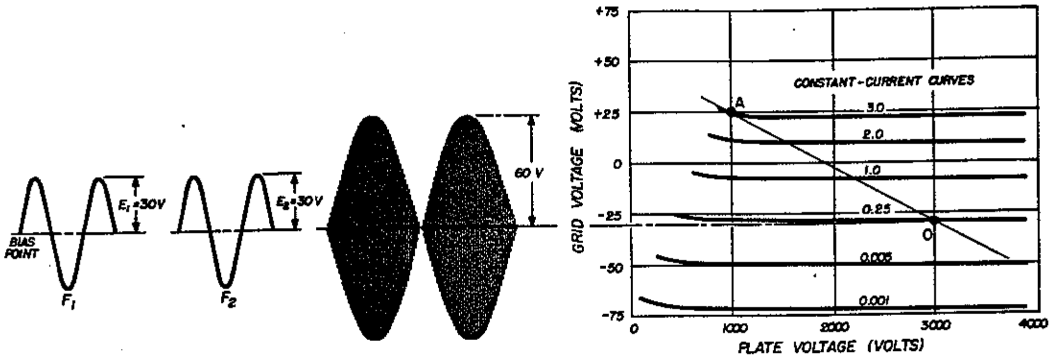

fig. 6. Two-tone condition.

The same holds true for a three-tone test signal. Note that the sum of the three individual tone-crest exciting voltages add in phase to drive the tube to the same peak current and peak plate voltage swing as that of the single-tone case (see **fig. 7**) so the PEP output is the same as the single- and two-tone examples.

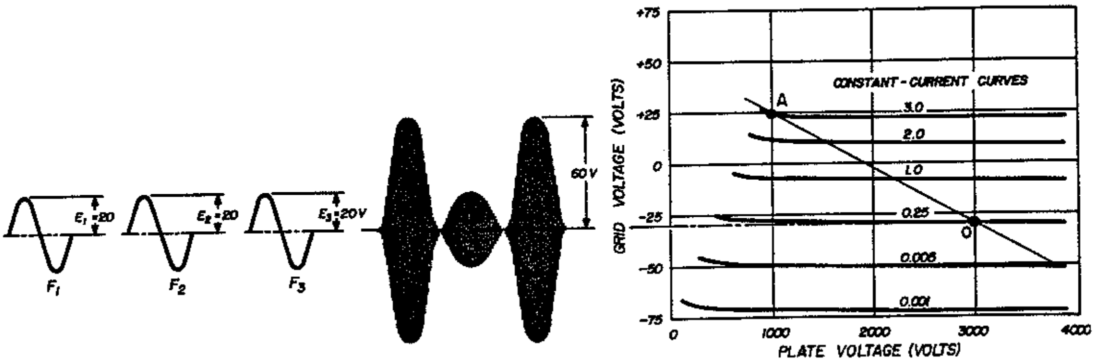

fig. 7. Three-tone condition.

These results (equal amplitude tones) may be summarized by the following expressions:

$$PEP = n\,P_{avg}$$
$$PEP = n^2\,P_t$$

Where P_{avg} is the average power of the composite signal, P_t is the average power in each tone, and n is the number of tones.

example

An fm repeater is to be designed to simultaneously rebroadcast one to eight channels. Each channel must have an average power output of 100 watts. How much peak envelope power must the linear amplifier deliver?

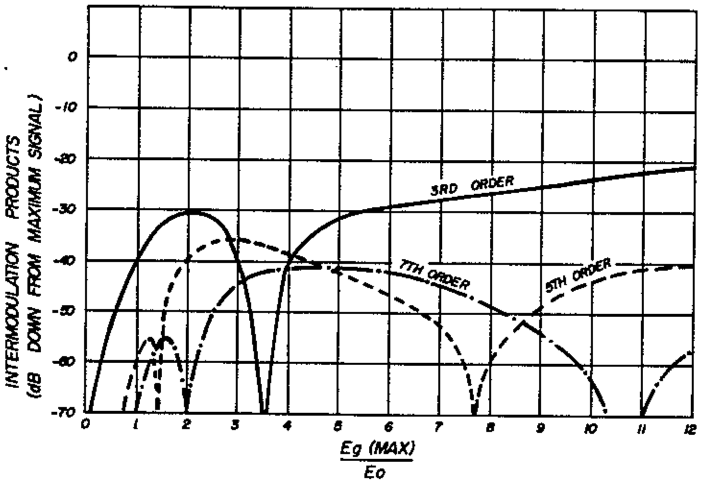

fig. 8. Graph showing intermodulation distortion products. As drive is increased, the various IMD products pass through maxima and minima. Misleading conclusions can be drawn if the equipment is tested near a cusp on the IMD curve where a particular IMD product drops to an extremely low level.

Each channel can be considered to be a single-tone signal. Therefore, the PEP of each channel is equal to the average power of each channel. The *maximum power output* requirement of the amplifier will be under the 8-tone condition. The average power output for the composite 8-tone signal will be 8 times the 100 watts-per channel power. Therefore, the linear amplifier must be capable of 800 watts of average power output.

The peak envelope power will be eight times the average power of the composite signal ($PEP = nP_{avg}$) or 6400 watts. A tube must be selected to deliver this peak-envelope and average power at an intermodulation distortion level compatible with the degree of interchannel crosstalk that can be tolerated.

measurement standards

To describe adequately the performance of a tube in single-sideband linear service, it is necessary to determine many parameters. The normal electrode voltages and currents must be specified as well as the two-tone currents, the operating point, peak envelope power and the magnitude of the intermodulation-distortion products. These parameters are defined as follows:

Peak envelope power is the root-mean-square power at the crest of the envelope. This term is usually shortened to PEP.

Idling plate current determined by the operating point is called the *zero-signal*

appendix 1

Approximate relationships between meter readings, peak envelope power and average power for class B or AB operation with one- and two-tone tests.

parameter	single-tone	two-tone
dc plate current	$I_b = \frac{i_{pm}}{\pi}$	$I_b = \frac{2i_{pm}}{\pi^2}$
plate input (watts)	$P_{in} = \frac{i_{pm}E_b}{\pi}$	$P_{in} = \frac{2i_{pm}e_p}{\pi^2}$
average output (watts)	$P_o = \frac{i_{pm}e_p}{4}$	$P_o = \frac{i_{pm}e_p}{8}$
PEP (watts)	$P_o = \frac{i_{pm}e_p}{4}$	$P_o = \frac{i_{pm}e_p}{4}$
plate efficiency	$N_p = \frac{\pi e_p}{4E_b}$	$N_p = \left(\frac{\pi}{4}\right)^2 \frac{e_p}{E_b}$

definition of symbols:

i_{pm} = peak of the plate current pulse (plate current pulse is not sinusoidal)

e_p =peak value of plate swing, assumed to be sinusoidal when tank-circuit has sufficiently high Q.

E_b = dc plate supply voltage

plate current and is designed I_{bo}.

The other two plate current values of significance are the *single-tone plate current* and the *two-tone plate current*. The ratio of single- to two-tone current is 1.57:1 in a true class B amplifier (180° plate conduction angle). For other classes of linear operation and for different zero-signal plate currents, this ratio varies from 1.1 to 1.57:1.

The standard method of specifying the magnitude of the distortion products is to specify the reduction in decibels of one product from one tone of a two-equal-tone signal.

For example, assume that a particular tube under a given set of operating conditions has third-order distortion products of −35 dB and fifth-order distortion products of −50 dB. This means that the third-order product has an amplitude of 35 dB below one of the two test tones and the fifth-order product has an amplitude 50 dB below one of the two test tones. (It is also correct to add the amplitudes of the two third-order products and compare them to the *sum* of the two tones. The decibel ratio is still the same as the example.)

It is *not* correct to compare one distortion product to the sum of the two tones; that is to say, the PEP value of the signal. The resulting distortion figure would be 6 dB better than the correct example (−41 dB rather than −35 dB and −56 dB rather than −50 dB).

Normally the tube under test is adjusted to the full drive condition, and all the pertinent parameters are measured. The drive signal is then reduced. At each test point, all the parameters are measured again. The resulting data can then be plotted as a function of drive voltage.

It should be noted that maximum intermodulation distortion does not necessarily occur at maximum drive level, and it can be shown mathematically that an intermodulation characteristic like **fig. 8** can be expected. In practice there is very good correlation between mathematical prediction and actual test results.

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