SECTION 6

OPERATING CONDITIONS FOR VARIOUS APPLICATIONS

6.1 ADJUSTMENT OF LOADING AND EXCITATION

In a typical transformer-coupled audio amplifier, the anode-to-anode load impedance required is given in the technical data sheet for the tube type under consideration or can be calculated. The secondary load impedance is normally defined by the application. It only remains to specify the turns ratio of the transformer.

Once the proper output transformer and secondary load are adjusted, the proper excitation is determined by the anode current. If a means is available to measure the grid voltage swing, this can also be used to indicate proper excitation.

In adjusting tetrode or pentode RF amplifier for proper excitation and loading, it will be noticed that the procedure is different, depending upon whether the screen voltage is taken from a fixed supply or a dropping resistor supply with poor regulation. In the case where both the screen supply and grid bias are from fixed sources with good regulation, the anode current is almost entirely controlled by the RF excitation. One should first vary excitation until the desired anode current flows. The loading is then varied until the maximum power output is obtained. Following these adjustments the excitation is then trimmed along with the loading until the desired control grid, and screen grid currents are obtained.

In the case of an RF amplifier where both the screen and grid bias are taken from sources with poor regulation, the stage will tune very much like a triode RF power amplifier. The anode current will be adjusted principally by varying the loading, and the excitation will be trimmed to give the desired control grid current. In this case the screen current will be almost entirely set by the choice of the dropping resistor. It will be found that excitation and loading will vary the screen voltage considerably and these should be trimmed to give about normal screen voltage.

The grounded-grid amplifier has been used for many years, but with the advent of new high power “zero bias” triodes it has become more common. To adjust the excitation and loading of a grounded-grid RF amplifier requires a slightly different procedure. A means of monitoring power output is usually necessary. The anode voltage (anode and screen voltage in the case of a tetrode or pentode) must be applied before the excitation. If this precaution is not followed, there is a very good chance of damage being done to the control grid. The loading is increased as the excitation is increased. When the desired anode current is reached the power output should be noted. The loading can be reduced slightly and the excitation increased until the anode current is the same as before.

If the power output is less than before, a check can be made with increased loading and less excitation. By proper trimming the proper grid current, anode current and optimum power output can be attained.

In a grounded-grid circuit the cathode, or input circuit, is in series with the anode circuit. Because of this, any change made in the anode circuit will have an effect on the input circuit. Therefore, the driver amplifier does not see its designed load until the driven stage is up to full anode current.

6.2 OPERATING VOLTAGES AND CURRENTS

The simplest way to get an idea of the capabilities of the tube, and the voltages and currents to be used on the various electrodes, is to refer to the technical data sheet for that tube type. A number of typical operating conditions are given for various classes of service. A great many other operating conditions are possible, but those in the data sheet are selected to show the maximum capabilities of the tube for different anode voltages. At no time should the maximum ratings for that class of service be exceeded.

As long as none of the maximum ratings of the tube are exceeded, a wide choice of voltages on the anode, screen, or grid is available and a wide range of anode current values may be chosen.

In referring to the characteristic curves of a tube type, it should be recognized that these curves are typical of a normal tube. As in all manufactured products, some tolerance is allowed. For all tube types manufactured there is an established test specification giving the most important parameter ranges used for the quality control of the product.

6.3 EFFECT OF DIFFERENT SCREEN VOLTAGES

Typical operating values for a tetrode or pentode for a particular value of screen voltage are given on the published technical data sheet. The screen voltage is not critical for most applications and the value used has been chosen as a convenient value consistent with low driving power and reasonable screen dissipation. If lower values of screen voltage are used, more driving voltage will be required on the grid to obtain the same anode current. If higher values of screen voltage are used less driving voltage will be required. Thus, high power gain can be had provided the circuit has adequate stability. Care should be observed that the screen dissipation limit is not exceeded. The value of screen voltage can be chosen to suit available power supplies or amplifier conditions.

The published characteristic curves of tetrodes and pentodes are shown for the commonly used screen voltages. Occasionally it is desirable to operate the tetrode or pentode at some screen voltage other than that shown on the characteristic curves. It is a relatively simple matter to convert the published curves to corresponding curves at a different screen voltage by the method to be described.

This conversion method is based on the fact that if all interelectrode voltages are either raised or lowered by the same relative amount, the shape of the voltage field pattern is not altered, nor will the current distribution be altered. The current lines will simply take on new proportionate values in accordance with the three halves power law. The method fails only where insufficient cathode emission or high secondary emission affects the current values.

6.4 THE THREE HALVES POWER LAW

For instance, if the characteristic curves are shown at a screen voltage of 250 volts and it is desired to determine conditions at 500 screen volts, all voltage scales should be multiplied by the same factor that is applied to the screen voltage (in this case, 2). The 1000 volt anode voltage line now becomes 2000 volts, the 50 volt grid voltage line 100 volts, etc.

The current lines then all assume new values in accordance with the 3/2 power law. Since the voltage was increased by a factor of 2, the Current lines will all be increased in value by a factor of $2^{3/2}$

or 2.8. Then all the current values should be multiplied by the factor 2.8. The 100 mA line becomes a 280 mA line, etc.

Likewise, if the screen voltage given on the characteristic curve is higher than the conditions desired, the voltage should all be reduced by the same factor that is used to obtain the desired screen voltage. Correspondingly, the current values will all be reduced by an amount equal to the 3/2 power of this factor.

For convenience the 3/2 power of commonly used factors is given in Figure 70.

VOLTAGE FACTOR	CURRENT FACTOR
0.25	0.125
0.50	0.35
0.75	0.65
1.00	1.00
1.25	1.40
1.50	1.84
1.75	2.30
2.00	2.80
2.25	3.40
2.50	4.00
2.75	4.60
3.00	5.20

Figure 70. Three-halves power of commonly-used factors.

6.5 BALANCE OF AMPLIFIERS

6.5.1 Push-Pull Amplifiers

The push-pull configuration utilizes two tubes with excitation applied 180° out of phase, and the outputs connected likewise. One advantage of using tubes in push-pull for an amplifier is that even order harmonics and even order combination frequencies are cancelled in the output.

Optimum performance from a push-pull RF amplifier requires careful balancing. The physical layout of a push-pull amplifier is substantially more demanding than that of a single-ended amplifier, and special matched components must be used for the tuned circuits. For this reason the push-pull configuration has lost favor in most modern RF amplifier designs.

Tubes are still employed in push-pull audio amplifiers. Tetrodes or triode-connected tetrodes in class AB are commonly used up to an output power of approx. 50 kW. Class B is acceptable if the small level of crossover distortion that accompanies that class of operation is acceptable.

Circuit diagrams of an RF amplifier using triodes in push-pull are shown in sec. 5.4.1.

In a push-pull RF amplifier, imbalance in the anode circuit or of anode dissipation is usually due to lack of symmetry in the RF circuit. Normally, the tubes are similar enough that such unbalance is not associated with the tube or its characteristics. This can readily be checked by interchanging the tubes in the sockets (provided both tubes have common dc voltages to anode, screen, and grid), and observing whether the unbalanced condition remains with the socket location, or moves with the tube. If it remains with the socket location, the circuit requires adjustment. If appreciable unbalance is associated with the tube, it is possible that one tube is not normal and should be investigated further.

The basic indicators of balance are the anode current per tube and the anode dissipation of each tube. It is assumed that the circuit applies the same dc anode voltage, dc screen voltage (if a tetrode or pentode), and dc grid bias to each tube from common supplies. Also, it is initially assumed that the anode circuit is mechanically and electrically symmetrical or approximately so.

Unbalance in a push-pull RF amplifier is usually caused by unequal RF voltages applied to the grids of the tubes, or by the RF anode circuit applying unequal RF voltages to the anodes of the tubes. The RF grid excitation should first be balanced until equal dc anode currents flow in each tube. Then the RF anode circuit should be balanced until equal anode dissipation appears on each tube, or equal RF anode voltage.

The balance of anode current is a more important criterion than equality of screen current (in a tetrode or pentode) or grid current. This results from the fact that tubes tend to be more uniform in anode current characteristics. However, the screen current is very sensitive to lack of voltage balance in the RF anode circuit and may be used as an indicator.

Once the dc anode currents per tube have been made equal by adjusting the RF grid circuit, the RF anode circuit can be adjusted to give equal anode dissipations. Or, if the tetrodes or pentodes have equal screen current characteristics, the RF anode circuit could be balanced until equal screen currents results. If the tubes differ somewhat in screen current characteristics, and the circuit has common dc supply voltages, the final trimming of the anode circuit balance may be made by interchanging tubes and adjusting the circuit to give the same screen current for each tube regardless of its location. Note that the dc grid current has not been used as an indicator of balance of the RF power amplifier. It is probable that after following the foregoing procedure the grid currents will be fairly well balanced, but this condition in itself is not a safe indicator of balance of grid excitation.

6.5.2 Parallel Tube Amplifiers

The previous discussion has been oriented toward the RF push-pull amplifier. The same comments can be directed to parallel tube RF amplifiers. The problem of balance to be certain each tube carries its fair share of the load must still be considered.

In audio power amplifiers operating in Class AB_1 or Class AB_2, the idle dc anode current per tube should be balanced by separate bias adjustments for each tube. In many cases some lack of balance of the anode currents will have negligible effect on the overall performance of the amplifier.

When tubes are operating in the idle position, close to cut-off, anode current cannot be held to a close percentage of tolerance. At this operating point, the action of the anode and screen voltages is in a delicate balance with the opposing negative grid voltage. The state of this balance is indicated by the anode current. Very minor variations of individual grid wires or diameter of grid wires can upset the balance, and it is practically impossible to control such minor variations during manufacturing. In many audio amplifier applications, especially where the larger power tetrodes are used, the circuit should be designed to permit the bias to be adjusted individually for each tube.

6.6 HARMONIC AMPLIFIER AND CONTROL OF HARMONICS

A pulse of anode current delivered by the tube to the output circuit contains components of the fundamental and most harmonic frequencies. To generate output power that is a harmonic of the exciting voltage applied to the control grid, it is merely necessary to resonate the anode circuit to the desired harmonic frequency. To optimize the performance of the amplifier, it is necessary to adjust the angle of anode current flow to maximize the desired harmonic. The shorter the length of the current pulse for a particular harmonic, the higher will be the anode efficiency; but the bias, exciting voltage, and driving power are also increased. If the pulse is too long or too short, the output power drops off appreciably.

The harmonic power output that is obtainable decreases with the order of the harmonic. The relative harmonic output obtainable from a given tube compared with normal Class C output with the same peak space current is approximately inversely proportional to the order of the harmonic. The table given in Figure 71 may be used to estimate performance of a harmonic amplifier.

HARMONIC	Optimum Length of pulse, electrical degrees at the fundamental frequency	Approximate Power output assuming that normal Class C output is 1.0
2	90-120	0.65
3	80-120	0.40
4	70-90	0.30
5	60-72	0.25

Figure 71. Anode-Current Pulse Length and Power Output of Harmonic Amplifiers.

The "Tube Performance Computer" described in Section 3 may be used to estimate the harmonic amplifier performance for tetrodes and pentodes because anode voltage has only a small effect on anode current. It has been found that the anode circuit efficiency of tetrode and pentode harmonic amplifiers is quite high. In triode amplifiers, if feedback of the output harmonic occurs, the phase of the voltage feedback usually reduces the harmonic content of the anode pulse, and thereby lowers the anode circuit efficiency. Since tetrodes and pentodes have negligible feedback, the efficiency of a harmonic amplifier is usually comparable to that of other amplifiers.

Also, the high amplification factor of a tetrode or pentode causes the anode voltage to have little effect on the flow of anode current, and it is easier to obtain anode pulses with high harmonic energies without using excessive grid bias. A well designed tetrode or pentode also permits large RF voltages to be developed in the anode circuit while still passing high peaks of anode current in the RF pulse. These two factors help further to increase the anode efficiency.

The previous discussion of harmonics has been for the situation where harmonic power in the load is desireable and has been the design objective. Normally, the generation and radiation of harmonic energy must be kept at a minimum in a fundamental frequency RF amplifier.

It is not generally appreciated that the pulse of grid current also contains harmonic frequency energy. Control of these harmonic energies may be quite important. The ability of the tetrode and pentode to isolate the output circuit from the input circuit for a very wide range of frequencies is important in avoiding feed-through of harmonic voltages from the grid circuit. An important part of this isolation is the fact that properly designed tetrodes and pentodes permit the construction of complete shielding in the amplifier layout so that coupling external to the tube is also prevented.

In RF amplifiers operating either on the fundamental or a desired harmonic frequency, the control of unwanted harmonics is very important. The following steps permit reduction of the unwanted harmonic energies present in the output circuit:

(a) The circuit impedance between anode and cathode should be very low for the high harmonic frequencies. This may be obtained by having some or all of the tuning capacitance of the resonant circuit close to the tube.

(b) Complete shielding of the input and output compartments.

(c) The use of inductive output coupling from the resonant anode circuit and possibly a capacitive or Faraday shield between the coupling coil and the tank coil, or a high frequency attenuating circuit such as a Pi, or Pi-L network.

(d) The use of low pass filters for all supply leads and wires coming into the output and input compartments.

(e) The use of resonant traps for particular frequencies.

(f) The use of a low pass filter in series with the output transmission line.

6.7 SHIELDING

In an RF amplifier the shielding between the input and output circuits must be considered. Triode amplifiers are more tolerant of poor shielding because power gain is relatively low. If the circuit layout is reasonable and no inductive coupling is allowed to exist, quite often the triode amplifier can be built without shielding and it will perform adequately. It would be better engineering practice to shield the input and output circuits. Even if the shielding is not necessary to prevent fundamental frequency oscillation, it will most certainly aid in eliminating any tendency toward parasitic oscillation. The higher the gain of an amplifier the more important the shielding.

6.7.1 Pierced Shields

Tetrode and pentode amplifiers require excellent shielding to prevent input to output circuit coupling. It is advisable to use non-magnetic materials such as copper, aluminum, or brass in the RF fields to provide the shielding. Quite often a shield must have holes through it to allow the passage of cooling air. In the LF and part of the HF range, the presence of small holes will not impair the shielding. As the frequency is increased the RF currents flowing around the hole in one compartment cause fields to pass through the hole. Currents are, therefore, induced on the shield in the other compartment. This type of problem can be eliminated by using holes which have significant length. A piece of pipe with a favorable length to diameter ratio as compared to the frequency of operation will act as a “waveguide beyond cutoff attenuator.”[19] If more than one hole is required to pass air, a material resembling a honeycomb may be used. The material is commercially available[20] and provides excellent isolation with a minimum air pressure drop. Several sockets manufactured by EIMAC have this waveguide beyond cutoff air path. These sockets allow the tube in the amplifier to operate at very high gain and up through VHF.

6.7.2 Metal Base Shells and Submounted Sockets

Some tetrodes and pentodes have metal base shells. The shell should be grounded by the clips provided with the socket. This completes the shielding between the output and input circuits since the base shell of the tube comes up opposite the screen shield within the tube itself.

19 Simon Ramo and John R. Whinnery “Fields and Waves in Modern Radio,” New York, Wiley, 1953.

20 Hexcel Products, Inc., 281 Tresser Blvd., Stamford, CT 203-969-0666, www.hexcelcomposites.com.

Some pentodes use this metal base shell as the terminal for the suppressor grid. If the suppressor is to be at some potential other than ground, then the base shell must not be dc grounded. The base shell would be bypassed to ground for RF and insulated from ground for dc.

There is a family of tetrodes and pentodes without the metal base shell. It is good practice for this type of tube structure to submount the socket so that the internal screen shield is at the same level as the chassis deck. This technique will improve the input to output circuit shielding. It is very important in submounting a tube that adequate clearance be provided around the base of the tube for passage of cooling air.

6.7.3 Compartments

By placing the tube and circuits in completely enclosed compartments and by properly filtering incoming supply wires, it is possible to prevent coupling out of radio frequency energy by means other than the desired output coupling.

Such filtering prevents the coupling out of energy which may be radiated or be fed back to the input or earlier stages to cause trouble. Energy fed back to the input circuit causes undesirable interaction in tuning, or self-oscillation. If energy is fed back to the earlier stages, the trouble may be greater due to the larger power gain over several stages.

Audio amplifiers using high gain tubes require similar layout consideration. Quite often in the design of an RF amplifier doors or removable panels must be used. The problem of making a good, low resistance joint at the discontinuity must be met. There are several materials available commercially for this application. Finger stock[21] has been used for many years. "Teknit"[22] is also a practical solution. Sometimes it is found that after the wiring has been completed, further shielding of a wire is required. There are various types of shielding tapes[23] that can be wound on as a temporary or even permanent solution.

21 Finger stock is manufactured by: Tech-Etch, Inc. 45 Aldrin Road, Plymouth, MA 02360; Laird Technologies 1 800.843.4556;.

22 "Teknit" is manufactured by: Technical Wire Products, Inc., 129 Dermody Street, Cranford, New Jersey.

23 Magnetic Shield Division, Perfection Mica Co., 742 N. Thomas Dr., Bensonville, Illinois 60106-1643.

6.8 DRIVE POWER REQUIREMENTS

The technical data sheet for a particular tube gives the approximate drive power required. As the frequency of operation increases and the physical size of the tube structure becomes large with respect to this frequency, the drive power requirement will also increase.

The drive power requirements of a grounded-cathode amplifier consists of six major parts:

(a) The power consumed by the bias source.

$$P_1 = Ic1\ Ec1$$

(b) The power dissipated in the grid due to rectified grid current.

$$P_2 = Ic1\ e_{cmp}$$

(c) The power consumed in the tuned grid circuit.

$$P_3 = i^2_{c_{rms}} R_{rf}$$

(d) The power loss due to transit time.

$$P_4 = \left(\frac{e_{c_{rms}}}{R_t}\right)^2$$

Where Rt is that part of the resistive component of the tube input impedance due to transit time.

$$R_t = \frac{1}{Kg_m f^2 T^2}$$

(e) The power consumed in that part of the resistive component of the input impedance due to the cathode lead inductance.

$$P_5 = \frac{e_g^2}{R_s}$$

Input resistance resulting from the inductance of the cathode lead equals

$$R_s = \frac{1}{\omega^2 g_m L_k C_{gk}}$$

(f) Power dissipated in the tube envelope due to dielectric loss.

$$P_6 = 1.41 f E_1^2 \epsilon$$

I_{c1} = d-c grid current
E_{c1} = d-c grid voltage
e_{cmp} = maximum positive grid voltage
$i_{c_{rms}}$ = r.m.s. value of r-f grid current
R_{rf} = r-f resistance of grid circuit
e_{crms} = r.m.s. value of r-f grid voltage
R_t = resistance due to transit time loading
K = a constant function of tube geometry
g_m = transconductance
f = frequency, in hertz
T = transit time, cathode to grid
R_s = cathode lead inductance input resistance loading
ω = $2\pi f$
L_k = cathode lead inductance in henries
C_{gk} = grid to cathode capacitance in farads
E_1 = voltage gradient in kilovolts per inch, r.m.s.

The total driving power in the VHF and UHF region is often greater than the grid dissipation capability of the tube.

6.9 VHF AND UHF OPERATING CONDITIONS FOR SATISFACTORY ANODE EFFICIENCY AND MINIMUM DRIVE

When operating a tube in the VHF and UHF region the driving power can usually be minimized without appreciably affecting the anode conversion efficiency, by the following steps:

(a) A minimum dc control grid bias should be used. Frequently, it is advisable to bring this down to approximately cut-off.

(b) A high value of dc screen voltage is advisable even though it appears to increase the fraction of the cycle during which anode current flows.

(c) Using the minimum RF excitation voltage necessary to obtain anode circuit performance, even though the dc grid current is considerably lower than one would expect at lower frequencies.

(d) The cathode lead inductance to the output and input circuits should be kept to a low value. This can be accomplished by using short and wide straps, by using two separate return paths for the input and output circuits or by proper choice of cathode bypass capacitor.

It has been found that the choice of driving conditions as indicated does not necessarily decrease the anode efficiency as much as at lower radio frequencies. The steps indicated should be tried experimentally to determine whether or not the anode circuit efficiency is appreciably affected. It is preferable to sacrifice anode efficiency somewhat and improve the life expectancy of the tube in the VHF and UHF region.

Optimum output power at these frequencies is obtained when the loading is greater than would be used at lower frequencies. Apparently the use of lower RF voltage in the anode circuit is desirable. Fortunately, this same condition reduces driving power and screen current (in the tetrode and pentode) and improves life expectancy.

6.10 COOLING TECHNIQUES

Adequate cooling of the tube envelope and seals is one of the principle factors affecting tube life. Deteriorating effects increase directly with the temperature of the tube envelope and seals. The technical data sheet for the particular tube type should be studied thoroughly with reference to the cooling requirements.

Even if no cooling is specified, ample free space for circulation of air around the tube is required or else some air must be forced past the tube.

Excess cooling will have only beneficial results and inadequate cooling is almost certain to invite premature failure of the tube.

Tubes operated in the VHF and UHF region are inherently subjected to greater heating action than tubes operated at lower frequencies. This results directly from the flow of larger RF charging currents into the tube capacitances, by dielectric losses, and through the tendency of electrons to bombard parts of the tube structure other than the normal grid and anode. Greater cooling is therefore required at these higher frequencies. The technical data sheet for the particular tube type specifies the maximum allowable temperature. For the forced air and water cooled tubes, the recommended amount of air or water is also specified in the technical data sheet. Both the temperature and quantity of coolant should be measured to be certain the cooling is adequate. The problem of making temperature measurements is severe.

6.10.1 Making Temperature Measurements

Thermocouples, contact pyrometers, and other devices sensitive to radiant heat may be used to make temperature measurements, but these devices are often not available or not suited to the particular conditions under which a measurement must be made. For this reason, EIMAC recommends the use of a temperature-sensitive paint such as “Tempilaq,” available from local laboratory supply houses in the United States and Canada, and manufactured by the Tempil Division, Illinois Tool Works, Hamilton Blvd., So. Plainfield, New Jersey 07080, www.tempil.com.

Tempilaq dries to a powdery coat after application. At its critical temperature it melts and virtually disappears. After subsequent cooling it has a crystalline appearance which adequately indicates that the surface with which it is in contact has exceeded the critical temperature. Each sample should be melted on a test piece so that the observer can familiarize himself with the appearance before and after the critical temperature has been passed.

Reliable temperature measurements can be made with Tempilaq provided that it is applied in very thin coats and over small areas of the surface to be measured. The substance as supplied by the manufacturer is too thick for use in the presence of forced-air cooling. It should be thinned, using only the thinner recommended by the manufacturer, and it should be applied with an air brush or atomizer through a paper mask to limit the area covered.

The manufacturer recommends the use of a well-diluted spray of Tempilaq, stating that the amount required to produce a reliable indication is virtually unweighable. This is particularly true when making measurements in the presence of forced-air cooling or on glass envelopes where radiant heat may be intercepted by the Tempilaq itself.

A convenient set of equipment for making measurements with these temperature-sensitive paints is an atomizer with several vials, each equipped with an air-tight cap. One vial may be filled with thinner for cleaning the atomizer, while the remainder may be filled with properly thinned Tempilaq sensitive to several different critical temperatures.

Considering the importance of tube temperatures, every design engineer should familiarize himself with the use of Tempilaq or some other similar substance. Measurements of this kind yield basic information sometimes obtainable in no other way.

6.10.2 Forced air and convection cooling

Some of the lower power vacuum tubes may be cooled by normal free convection around the base and envelope of the tube. Figure 72 illustrates a typical air cooling system.

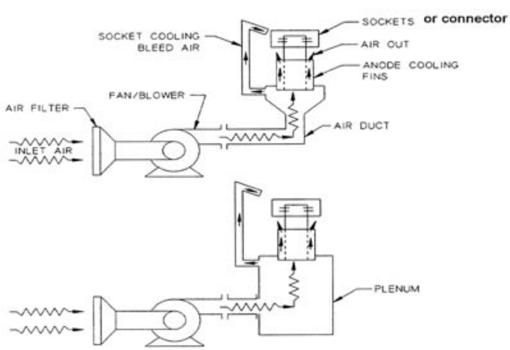

Figure 72. Typical air cooling system.

The tube and socket must be mounted in such a position as to allow unobstructed air flow. See Figures 73 and 74.

If the flow of cooling air is upward it will be consistent with the normal flow of convection currents. In all cases the socket is an open structure or has adequate vent holes to allow cooling of the base end of the tube. Cooling air enters through the grid circuit compartment below the socket through a screened opening, passes through the socket to cool the base end of the tube, sweeps upward

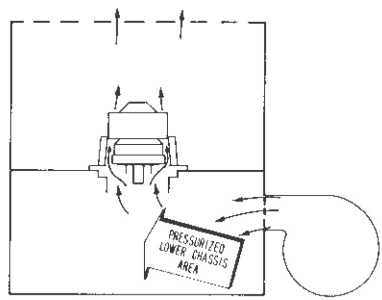

Figure 73. Tube mounting providing cooling, shielding and isolation of output and input compartments.

to cool the envelope and enters the output circuit compartment. The output compartment also has a mesh-covered opening which permits the air to vent out readily. These arrangements apply whether the tube is cooled by forced air or convection circulated air. If the tube is to be forced-air cooled, a suitable fan or blower is used to pressurize the compartment below the tubes. No holes should be provided for some air to pass from the lower to the upper compartment other than the passages through the socket and tube base. Some pressure must be built up to force the proper amount of air through the socket. In the case of convection cooling, open louvers or screened areas permit ready entrance of cool air, and all access holes or vents should have large areas to provide a minimum resistance to the flow of air.

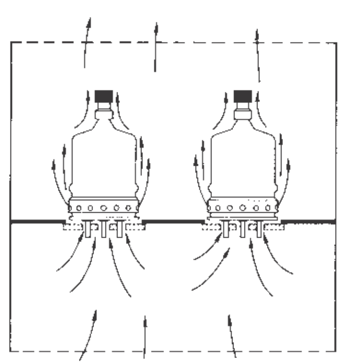

Figure 74. Chassis mounting providing cooling, shielding and isolation of output and input compartments.

The method of supplying the cooling air to the tube, shown in Figures 73 and 74, has worked successfully, provided the desired flow is obtained. It is preferred over methods which try to force cooling air transversely across the tube base.

In many cases, there are complete air system sockets and chimneys designed specifically for a tube or family of tube types. The technical data sheet for each tube type specifies the recommended socketing for adequate cooling.

Figure 75 Example of a badly overheated tetrode. The anode fins are badly oxidized and distored because of inadequate air flow.

The technical data sheet specifies the back pressure, in inches of water, and the cubic feet per minute required for adequate cooling. In an actual application the back pressure may be measured by means of a simple manometer. This consists of a simple U-shaped glass tube partially filled with water (see Figure 76), which is very useful in measuring low pressure values in connection with air flow. If an air pressure (P) of low value is introduced by connecting the air hose to the left branch of the U, the value of this pressure in inches of water column may be determined by measuring the height (h) between the two water levels.

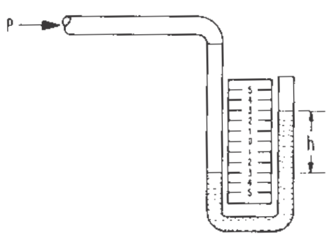

Figure 76. Measuring back-pressure[24].

24 See www.dwyer-inst.com for information about manometer theory and applications.

Forced-air cooling systems are capable of removing approximately 50 Watts per square centimeter of effective internal anode area.

6.10.3 Use of Cooling Airflow Data

EIMAC graphically presents minimum cooling airflow requirements for its large external anode tubes in the form of Total Power Dissipated in Watts/Tube Temperature Rise in degrees Centigrade (Pt/ΔT) **versus** Mass Airflow Rate in pounds of air per minute (M). These graphs are used in calculating the cooling requirements listed in the data sheets and copies are available from EIMAC.

The graphs apply to a specified tube and socket-chimney combination; further, the direction of airflow is specified. When reverse airflow, i.e., anode-to-base, is to be used, cooling requirements are sharply increased. This is because the air applied to the tube's base seals has already been heated by its passage through the anode cooler, losing much of its cooling effectiveness.

The procedure for using these graphs to determine the minimum cooling requirements is presented in the following:

(a) The total power dissipated (Pt) is determined by adding all of the power dissipated by the tube during operation in its particular installation. This includes anode and filament dissipations plus maximum anticipated grid and screen dissipations where applicable.

Example

Anode Dissipation	5000	Watts
Filament Dissipation	350	
Screen Dissipation	100	
Grid Dissipation	50	
Total Dissipation (Pt):	5500	Watts

(b) The tube-temperature rise (ΔT) is found by taking the difference between the maximum-rated tube temperature specified in the appropriate data sheet and the maximum air inlet temperature expected.

Example

Assume maximum tube temperature rating = 250°C
Expected maximum cooling air inlet temperature 50°C
Safety margin = 25°C (advisable; not required but recommended)

ΔT = 250-(50 + 25) = 175°C

Thus: Pt/ΔT = 500/175 = 31.4 Watts/ºC

(c) From EXAMPLE Cooling Airflow Requirements shown in Figure 77, Pt/ΔT = 31.4→7.9 lbs/min mass airflow rate. This is the mass airflow rate required at any altitude and for the given inlet air temperature to assure a maximum tube temperature of 225°C (250°C rating, minus 25°C safety margin) when the tube is dissipating a total of 5500 Watts. Volumetric airflow and pressure drop requirements, however, vary with altitude and inlet air temperature.

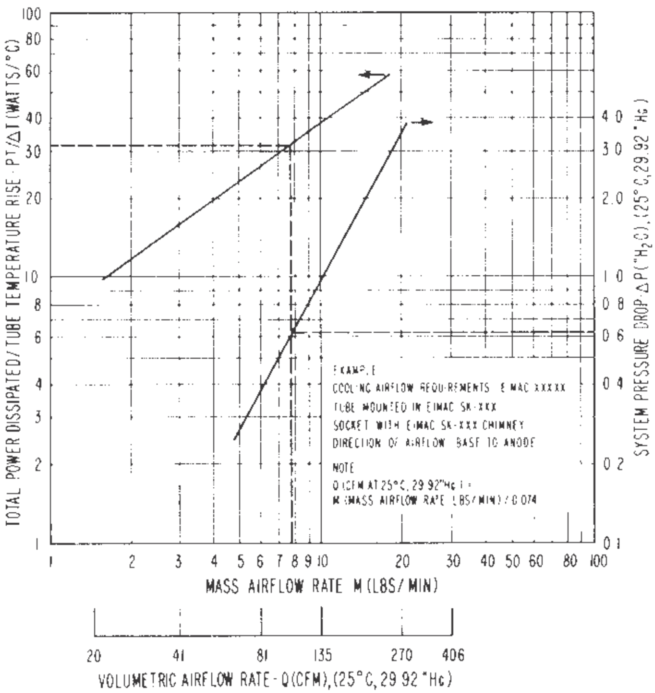

Figure 77. Cooling Airflow Requirements

(d To convert the mass airflow rate M (lbs/min) to volumetric airflow rate Q (cfm) at 25°C and at sea level, divide the mass airflow rate by the density of air at 25˚C and 29.92 inches Hg (In-Hg).

Note that the density of air = 0.737 x In-Hg/(273 + °C)lbs /ft^3.

Example

Density (25°C, 29.92 In-Hg) = 0.737 (29.92)/(273 + 25)

= 0.074 lbs /ft^3

Q = 7.9/0.074 = 106.8 CFM (25°C, 29.92 In-Hg)

(e) The curve on the right side of the graph in Figure 77 is the pressure drop (ΔP) in inches of H_2O across the tube and its specified socket-chimney combination, and is valid at **25°C at sea level only.**

Example

Q = 106.8 CFM (7.9 lbs/min) requires a pressure drop

ΔP = 0.61 H_2O^{in} (25°C, 29.92 In-Hg)

(f) To adjust the 25°C sea-level laboratory test conditions to any other atmospheric (socket-inlet) condition, multiply both the Q and ΔP values by the ratio of this laboratory standard density (0.074 lbs/ft^3; 25°C at sea level) to the density at the new socket-inlet condition.

Examples

1) The installation requirements for the EXAMPLE tube with 50°C socket inlet air and at sea level (29.92 In-Hg) are:

Density (50°C, 29.92 In-Hg) = 0.737 x (29.92)/(273 + 50) = 0.0683 lbs/ft^3

Density ratio = 0.074/0.0683 = 1.084

Q = 1.084 x 106.8 = 115.5 CFM

ΔP = 1.084 x 0.61 = 0.66 in-H_20

(2) The installation requirements for the EXAMPLE tube with 25°C socket inlet air and at 10,000 feet (20.58 In-Hg) are:

Density (25°C, 20.58 In-Hg) = 0.737 x(20.58)/(273 + 25) = 0.0508 lbs/ft

Density ratio = 0.074/0.0508 = 1.455

Q = 1.455 x 106.8 = 155.5 CFM

ΔP = 1.455 x 0.61 = 0.89 in-H_2O

(3) The installation requirements for the EXAMPLE tube with 50°C socket inlet air and at 10,000 feet (20.58 In-Hg) are:

Density (50°C, 20.58 In-Hg) = 0.737 x(20.58)/(273 + 50) = 0.0469 lbs/ft^3

Density ratio = 0.074/0.0469 = 1.573

Q = 1.576 x 106.8 = 168.5 CFM

ΔP = 1.578 x 0.61 = 0.96 in-H_2O

(g) A shorter method may be used to correct the 25°C sea-level requirements to both a different temperature and/or barometric socket inlet condition.

These corrections are made by multiplying the Q and ΔP values (determined in Examples 1 through 3) by the appropriate correction factors listed below:

Socket Inlet Air Temperature (°C)	Q and ΔP Correction Factor
0	0.917
5	0.933
10	0.950
15	0.967
20	0.983
25	1.000
30	1.017
35	1.034
40	1.051
45	1.067
50	1.084

Socket Inlet Air Pressure (''Hg)	Altitude (Ft)	Q and ΔP Correction Factor
29.92	0	1.00
24.90	5,000	1.20
20.58	10,000	1.46
16.89	15,000	1.77
13.75	20,000	2.17
11.10	25,000	2.69
8.89	30,000	3.37
7.04	35,000	4.25

Example

The installation requirements for the EXAMPLE tube with 50°C socket inlet air and at 10,000 feet (20.58 In-Hg) are:

Q = 1.084 x 1.46 x 106.8 = 168.5 CFM
ΔP = 1.084 x 1.46 x 0.61 = 0.96 In-H_2O

(h) Figure 78 is a graph of the combined correction factors that can bill applied to the 25°C sea-level information for land-based installations located at elevations up to 10,000 feet, and for socket-inlet air temperatures between 10°C and 50’C.

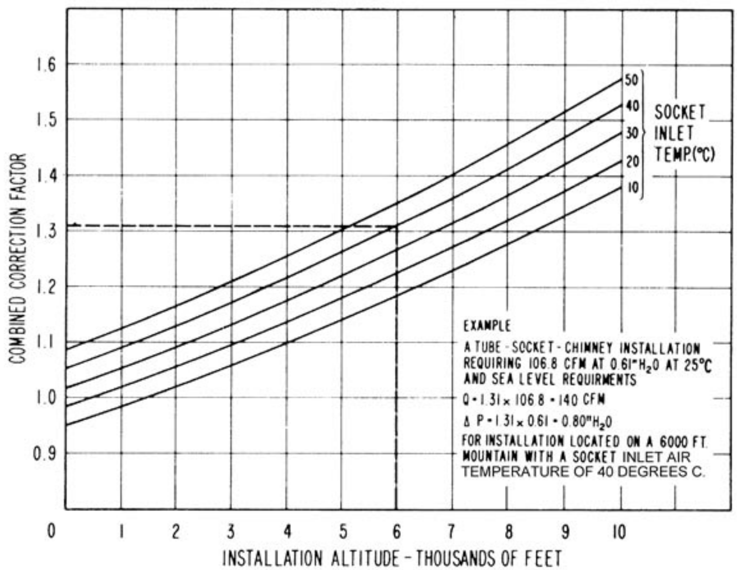

Figure 78. Combined correction factors for land-based installations.

Example

The installation requirements for the EXAMPLE tube with 50ºC socket inlet air at 10,000 feet are:
Q = 1.579 x 106.8 = 168.5 CFM

ΔP = 1.579 x 0.61 = 0.96 In-H_2O

Good engineering judgment must be used when applying altitude and temperature corrections to the 25°C sea-level cooling requirements for airborne installations. Although the air outside the aircraft may be very cold at high altitudes, the air actually entering the tube socket may be many degrees warmer. This inlet temperature (and pressure) is affected by each installation design (compressed, ram, static, or recirculating air in a pressurized heat exchanger).

Figure 79 is a convenient curve used to convert Mass Airflow Rate (lbs/min) into volumetric airflow rate (cfm) at 25°C and sea-level.

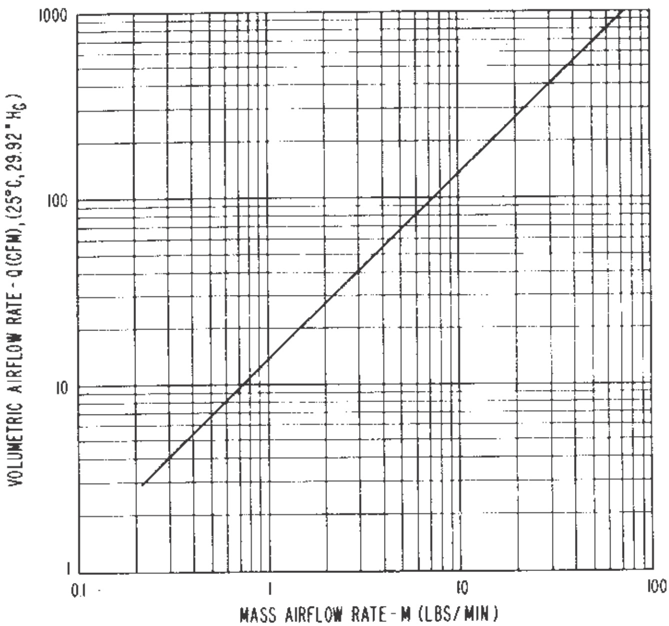

Figure 79. Conversion of mass airflow rate to volumetric airflow rate.

6.10.4 Blower Selection for Elevated Tube Installations

In the section immediately preceding, a method of determining minimum air-cooling requirements for external anode tubes was described, pertaining to any altitude and air temperature. Since most blower manufacturers furnish catalog data on their products in the form of volumetric airflow, Q (cfm) versus Operating Back Pressure, ΔP (inches of water) for **sea level conditions only,** the information gained by the foregoing procedure cannot be compared directly with the data furnished by the blower manufacturers, for the purpose of selecting the proper blower. The following method is recommended for use in selecting a blower for altitude applications from existing blower catalog data:

(a) Determine the Q and ΔP requirements for the tube-socket-chimney combination for an ambient air temperature of 25ºC at sea level. Include estimated ΔP of duct and filter.

(b) The system's corrected Q and ΔP requirements for the actual inlet temperature and altitude conditions are determined by multiplying by the correction factor shown in Figure 78.

(c) Again multiply the ΔP, but not the Q, requirement by the correction factor cited in Step b.

(d) The corrected Q factor and doubly-corrected ΔP value are then used to select a blower from the manufacturer's published sea-level curves. Although this blower will overcool the tube at sea level when operated in an ambient temperature of 25°C, it will provide adequate cooling at the actual inlet temperature and altitude conditions.

An example:

Given: A tube-socket-chimney requires 100 CFM at 1.0 in-H_20 at 25°C and sea level. (Normally determined as per step a).

Required: Determine the requirements for selecting a blower from manufacturer's catalog data (25°C, Sea Level Conditions) to insure that the system is adequately cooled in a 40°C ambient air temperature at an altitude of 8000 feet.

Solution: Step 1) Given

Step 2) From Fig. 78, it is determined that the correction factor for a combined environment of 8000 feet altitude at 40˚C inlet temperature is 1.42.

The corrected Q and ΔP is then,
Q = 1.42 x 100 = 142 CFM
ΔP 1.42 x 1.0 = 1.42 In-H_2O

Step 3) The doubly corrected ΔP is then,
$\Delta P = 1.42 \times 1.42 = 2.02$ in-H_20

Step 4) The blower selected from the manufacturer's catalog must be capable of delivering 142 CFM at 2.02 in-H_20 in an ambient temperature of 25°C at sea level in order that the tube socket-chimney system will be supplied with 142 CFM at 1.42 in-H_20 at 40°C and 8000 feet.

For further information pertaining to sub-critical air flow through an orifice, refer to MARKS ENGINEER'S HANDBOOK, 5th edition, pg. 334.

6.10.5 Water Cooling

Three types of water cooling techniques are used for power grid tubes, direct anode water cooling, vapor phase cooling and multiphase cooling.

Water-cooled tubes depend upon an adequate flow of water to carry away heat fast enough to maintain the cooled parts at a safe operating temperature. The recommended flow as specified by the technical data sheet should be maintained at all times when the tube is in operation. Inadequate flow of water at high temperature may cause formation of steam bubbles at the anode surface where the water is in direct contact with it. This can contribute to premature tube failure, or "burnout".

By electrolysis and scale formation, hard water may cause a gradual constriction of some part of the water system. Therefore, water flow and plumbing fittings must be inspected regularly. The fittings on the positive potential end of an insulating section of hose or ceramic water coil or column are particularly subject to corrosion or electrolysis unless they have protective "targets." Targets should be checked periodically and replaced when they have disintegrated.

Cooling water temperature is important. The tube technical data sheet should be consulted to be sure operation is within safe limits.

Purity of cooling water is important. The specific resistivity must be maintained at 1 megohm-cm minimum at 25°C. Distilled or de-ionized water should be used and the purity and flow protection should be periodically checked to insure against excessive degradation. Oxygen and carbon dioxide in the coolant will form copper oxide reducing cooling efficiency and electrolysis may destroy the coolant passages. In addition, a filter screen should be installed in the tube inlet line to trap any circulating debris which might clog coolant passages within the tube.

If the air is humid and the cooling water is cold, condensation accumulates on the surfaces of all pipes, tube jackets and other parts carrying water. This condensation may decrease surface leakage resistance, or drops of water may fall on some electrical component and cause erratic operation or failure. Some means is then necessary to control the temperature of the incoming water to keep it above the dew point. Control is rather easy in a closed cooling system, but in a system which employs tap water and drains the exhaust water into a sewer, control is difficult.

Connecting lines should be of an insulating material such as polypropylene, but chlorinated polyvinyl chloride (CPVC) is also acceptable and is stronger.

Circulating water can remove up to 1000 Watts per square centimeter of effective internal anode area. In practice, the temperature of water leaving the tube is limited to 70°C to preclude the possibility of spot boiling. This water is then passed through a heat exchanger where it is cooled to 30°C–40°C before being pumped over the tube anode again.

Refer to the EIMAC Application Bulletin 16 for additional details concerning liquid cooling systems.

6.10.6 Vapor-Phase Cooling

Vapor-phase cooling offers some advantages over water cooling systems by exploiting the latent heat of the evaporation of water. Raising the temperature of one gram of water from 40°C to 70°C (as in a water system) requires 30 calories of energy. **Transforming one gram of water at 100°C to steam vapor requires 540 calories.** In a vapor-cooling system, then, a given quantity of water will remove nearly twenty times as much energy as in a water-cooling system. Power densities as high as 135 Watts per square centimeter of effective internal anode surface have been attained through vapor cooling.

A typical vapor-phase installation consists of a tube with a specially designed anode immersed in a “boiler” filled with distilled water.

When power is applied to the tube, anode dissipation heats the water to I00°C; further applied energy causes the water to boil and be converted into steam vapor. The vapor is passed through a condenser where it gives up its energy and is converted back into the liquid state. This condensate is then returned to the boiler, completing the cycle. The result is a system that reduces the water flow requirement nearly 20 times and due to the thermo-syphoning action which results in a natural circulation of the water, eliminates the need for the pump required in a circulating water system. A bonus effect of vapor cooling is almost complete silence during operation.

A dramatic improvement over water-cooling systems is a reduction in the size of the condenser required. A condenser of any given thermal capacity can be reduced in size if the mean temperature gradient (Δ Tm) between the cooled liquid and the secondary coolant can be increased. In a practical water-cooling system like the one just described, water enters the heat exchanger at 70°C and leaves at about 40°C, the mean temperature being 55°C. With air as a secondary coolant (or heat sink) at about 30°C, there is a mean temperature differential, Δ Tm, of 25°C. In a typical vapor cooling system, vapor enters the condenser at 100°C, and water leaves at 100°C, resulting in a mean temperature of 100°C. The mean temperature differential Δ Tm then between the steam-water and air is now 100°C -25°C = 75°C, or **three times that of the water-cooled system.** Tests at EIMAC have confirmed this and have shown that heat exchanger equipment for a vapor-cooled system will require only about one-third to one-quarter the capacity associated with water cooling systems.

Where air-cooled condensers are preferred, this higher thermal gradient can be exploited in reducing the size of condenser equipment and in lowering the blower horsepower requirement. In some instances where sufficient area is available, natural convection alone is used to cool the steam condensers, resulting in complete elimination of the condenser blower.

Where water is preferred as the secondary coolant, similar ratios apply and water consumption is drastically reduced. For example, a water cooling system at the 100 kW dissipation level will require about 100 cubic feet of secondary water per hour, or 500,000 cubic feet over 5000 hours. With vapor-cooling, this is reduced to one-third, a savings of 333,333 cubic feet. With a water cost of $19.00 per 1000 cubic feet, about $6300 in water cost alone is saved over a 5000 hour period. In addition, a five-horsepower pump is eliminated. This pump requires about 25,000 kW-hr of electrical power over the same period, at a cost of about $2500.

Thus the vapor-cooling system would save the user about $8800 in operating costs over a 5000 hour period.

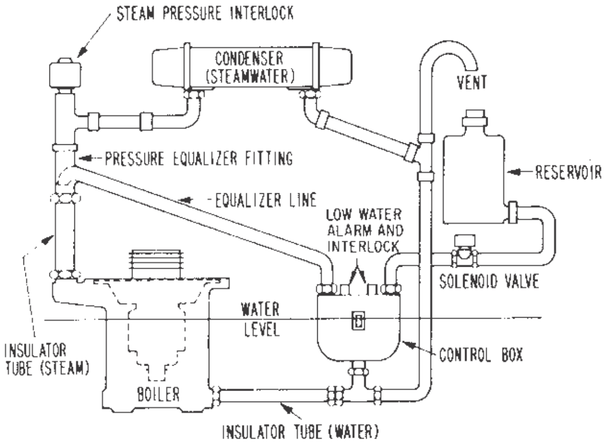

Figure 80. Typical vapor-phase cooling system.

(1) INSTALLATION NOTES

A typical vapor-phase cooling system is shown in Figure 80. It consists of the power tube, boiler, condenser, insulating tubing, control box, reservoir, and associated plumbing. Detailed installation suggestions for the various components are discussed below.

Boiler—The boiler supports the power tube and contains the water used for cooling. In addition, it acts as the high voltage anode connector. The boiler should be mounted so that the axis of the tube is vertical. For effective cooling, the tilt should be limited to less than 2° to insure that the anode is covered with water and the steam outlet is clear.

Figure 81. EIMAC vapor-cooled tubes for mounting in boilers.

The tube's anode flange must seal securely against the o-ring provided on the boiler. A locking flange presses the anode flange against the o-ring for a vapor-tight seal. The steam outlet at the top of the steam separation chamber on the boiler and the water inlet at the bottom of the boiler are equipped with fittings for attaching the pyrex insulating tubing. A "target" to inhibit electrolytic action is provided in the inlet water fitting.

Since in most cases the boiler is at high potential relative to ground, it must be electrically insulated from the rest of the system. It should be mounted on insulators and the steam and water connections should be made through pyrex insulating tubing. Boilers can be constructed with provisions for mounting two or three tubes in parallel. These would contain single water inlet and steam outlet fittings.

Insulating Tubing—Length of the steam and water insulating lines will vary with individual installation requirements, but will always be shorter than would be needed in a circulating water system. The length of the insulating tubing is dependent on the voltage to be applied, the purity of the water, and the volume of returned cooling water. In the vapor-cooling system, water is constantly being re-distilled, there is a minimum of contamination, and only pure distilled water is introduced into the boiler. In addition, the water inlet line is of smaller diameter—because of the low water flow rate—and has inherently higher resistance. Therefore, a two-foot section of pyrex tubing has the capability of preventing voltage flashover up to 2° kV, and will also have negligible leakage current. Because of the excellent insulating properties of steam (and the purity of any condensate) the outlet steam line can be made equally short.

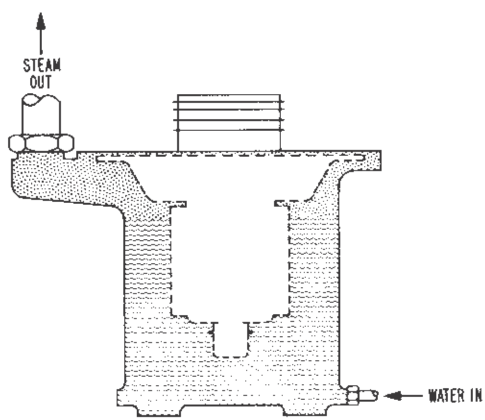

Figure 82 Cutaway of "classic" boiler and tube combination.

Control Box - The control box serves as a partial reservoir, and is an air-tight vessel containing an overflow siphon and two float switches. When the water level drops approximately 1/4” below the recommended level, the first switch is closed. It may at the same time be used to activate a solenoid-controlled water valve to admit more distilled water from an external reservoir, and/or actuate a warning alarm.

The second float switch is operated if and when the water level should drop approximately 1/2” below the optimum level. This would be tantamount to a water failure, and the switch would be used to open the control circuit interlocks and remove tube power.

For the control box to perform its protective function properly, its water level mark must be precisely level with the water level mark on the boiler. For electrical reasons, the control box will generally be mounted some distance from the boiler, and therefore leveling of the two components should be carefully checked during installation. Figure 82 shows a cutaway drawing of a “classic” boiler and tube combination, and Figure 83 is a cutaway drawing of a control box, showing the position of the float switches and the overflow pipe.

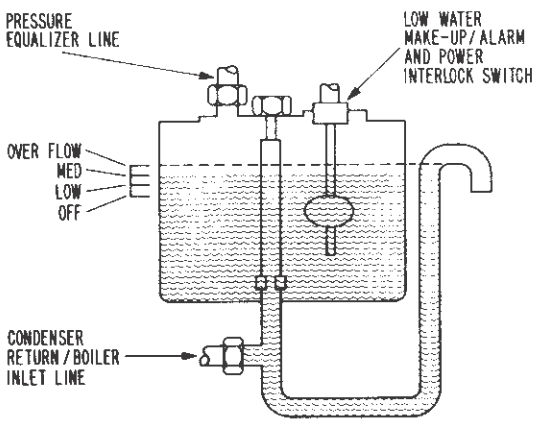

Figure 83. Cutaway view of typical Control Box showing position of float switches and overflow pipe.

The control box also serves a secondary function as a reservoir. During extended operation, some quantity of water and steam is being circulated through the condenser, and some will be lost through the air vent. The amount is, of course, dependent on the size of the system. The water level in the boiler will gradually drop. The use of the control box as a reservoir minimizes this effect. In large or multiple-tube installations, the use of an auxiliary reservoir connected to the control box is recommended to increase the ratio of stored water to circulating water and steam. Where it may be necessary to operate multiple tubes at different physical elevations, individual control boxes are required. A multiple-tube system is shown in Figure 84.

Equalizer Line—In order for the control box to "see" the same pressure conditions that exist in the boiler, the vapor-phase system should be fitted with an equalizer line. This length of tubing connects the steam side of the system with the top of the control box. As a partial steam pressure begins to build up in the boiler, the equalizer line allows this same pressure to appear in the control box. Steam pressure is low—less than 0.5 psi above atmosphere—but would introduce error in the control box water level unless equalized.

The fitting used to connect the equalizer line to the steam outlet tube must be constructed to prevent a venturi effect from developing

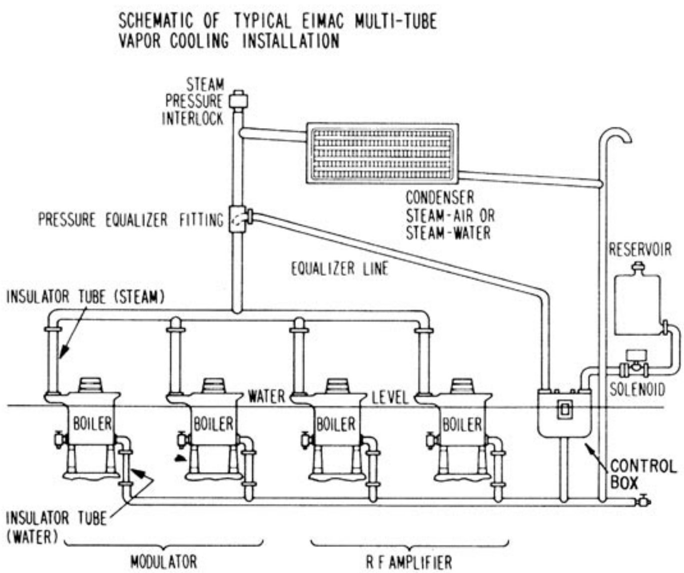

Figure 84. Typical 4-tube vapor cooling system with common water supply.

because of the velocity of the vapor. This is best accomplished by directing an elbow within the adapter fitting toward the boiler, as shown in Figure 85.

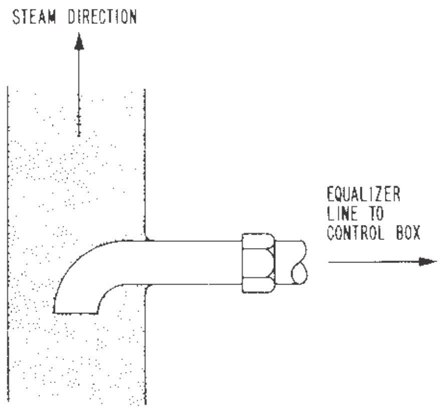

Figure 85. **Cutaway of pressure equalizer fitting.**

Condensers—Both air-cooled and ware available for vapor-cooling systems. Condensers should be chosen with good reserve capabilities and low pressure drop. The air-cooled and water-cooled condensers may be mounted in any position, providing they allow the condensed water to flow freely by gravity to the boiler return line. Water must not be allowed to stand in the condenser where it might cause back-pressure to the entering stream.

The condenser should be mounted above the level of the boiler(s) so that water will drain from it to the boiler return line. Where it is necessary to mount the condenser at a lower physical level than the system water level, an auxiliary pump should be used to return water to the boiler. This arrangement is recommended for the "steam-out-the-bottom" boiler system to be discussed later under "Alternate Vapor-cooling Systems." A "steam-out-the-bottom" system is shown in Figure 86.

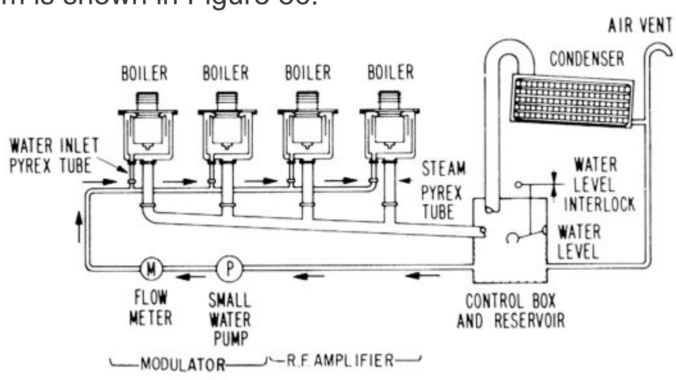

Figure 86. **Typical 4-tube system using "steam-out-the-bottom" boilers.**

Pressure Interlock—It is suggested that the use of a steam pressure interlock switch on the steam or inlet side of the condenser is advisable. This switch, set at about 0.5 lbs. per square inch, is used as a power interlock that senses any abnormal steam pressure due to constrictions in the condenser or piping.

Piping—Piping should be of copper or glass throughout the system. The steam piping should be the same diameter as the pyrex tube from the boiler. The size is dependent on power level and the volume of generated steam, and will range from 1-3/4” at the 8 kW level to 6” for the 250 kW level of dissipation. The steam path should be as direct as is practical and must be sloped to prevent condensate from collecting at some low point where it might cause backpressure. All low spots should be drained back to the inlet water line.

Water return piping from the condenser to the control box will vary from 3/4” to 1-3/4” in diameter, depending again on the power level. This tubing should be the same diameter as the boiler inlet water fitting. It should be sloped so that water or vapor pockets do not exist, and must allow the condensate to return by gravity to the control box and the boiler. A vent to air on the outlet side of the condenser should be incorporated to maintain the water side of the system at atmospheric pressure. Provisions for draining the distilled water should be provided at the system’s lowest level.

The equalizer line should also be sloped from the adapter fitting on the steam line to the top of the control box. This will allow the condensate to return to the control box.

Automatic Refilling System—Figures 80 and 86 show typical vapor-cooling systems with provisions to provide additional water to the control box. An auxiliary reservoir is connected through a solenoid-operated water valve to the control box. When accumulated water loss due to evaporation causes the water level in the boiler and the control box to drop about 1/4” below normal, the first float switch in the control box closes and actuates the solenoid-controlled valve to permit makeup water to enter the system. When the proper level is restored, the switch opens, the valve closes, and the flow of makeup water is stopped.

6.10.7 Maintenance

Maintenance problems associated with circulating water systems are practically eliminated through vapor cooling systems. As mentioned earlier, **systems can be designed to eliminate all rotating machinery or moving parts.**

System cleanliness does, however, require periodic attention. The glass insulator tubes should be inspected occasionally to be sure they contain no deposits which might cause voltage flashover. Water conductivity should be checked periodically by measuring the dc resistance, as in a typical circulating water system. Water should be replaced if its dc resistance drops below 20,000 ohms/cm2.

In practice, the vapor-cooling system will remain cleaner longer than a water-cooled system. In the vapor-cooled boiler, the water is continually being redistilled and only pure water is introduced at the bottom of the boiler. Any contaminants will tend to remain in the boiler itself, where they can be easily removed. The periods between equipment shutdowns for draining and cleaning will be at least twice as long for the vapor-cooling system because of this inherent self-cleaning action.

Each time a tube is removed or replaced, the rubber o-ring between the boiler and the tube should be inspected and replaced if necessary. At the same time the inside of the boiler and the control box should be inspected and cleaned if necessary.

The electrolytic target should be replaced whenever its metallic end is no longer visible in the inlet water line.

6.10.8 Alternate Vapor Cooling Systems

The system described thus far is the so-called “classic” system which consists of a separate tube, boiler, condenser, and level control box. Variations on these schemes are numerous. One such alternate system, offered for use with the larger tubes, uses a “steam-out-the-bottom” boiler. This configuration makes it possible to keep the steam and water systems, plus the plumbing, below the tubes. Figure 86, shows a typical “steam-out-the-bottom” system and Figure 87 shows a boiler associated with this particular cooling technique. This approach has the advantages of keeping the plumbing away from the input circuitry.

A small water pump circulates a continuous flow of water over a weir, or baffle, in the boiler, maintaining a constant water level. Generated steam is forced under slight pressure out-of-the-bottom of the boiler, through an insulator tube in the condenser. Water from the condenser flows into the control box before being pumped back into the boiler. Protective devices must include a water flow interlock and the usual level control in the control box to insure an adequate water supply.

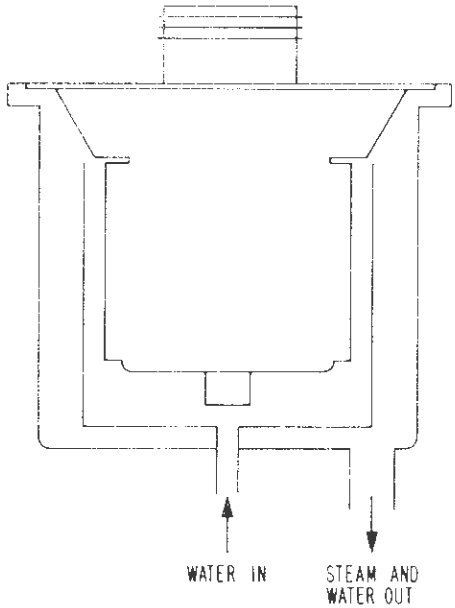

Figure 87. Cutaway view of "steam-out-the-bottom" boilers.

6.10.9 Multiphase Cooling

Another liquid/vapor-based cooling technique is called multiphase cooling. Multiphase cooling utilizes a combination of pure cool water cooling and a 100% heated surface boiling condition, as found in vapor phase cooling. Multiphase cooling is capable of anode surface heat transfer rates up to 2.5 kW/cm^2. This is several times the thermal dissipation rates achieved by standard 100% vapor-phase techniques.

Multiphase cooling is accomplished by pumping cooling water through narrow channels in the anode at relatively high velocities, wherein part of the liquid phase water in contact with the anode channel walls flashes to steam phase bubbles. These steam phase bubbles are instantly removed from the heated anode surface by the high velocity bulk liquid water. The extracted steam bubbles then condense in the cooler bulk water flow before leaving the tube. Although the bulk cooling water may enter the tube at below 50ºC and exit at less than 90ºC, local surface boiling occurs at spots along the heated surface of the anode.

No steam venting is necessary with multiphase cooling because the steam generated is condensed back into the bulk cooling water before leaving the tube.

Multiphase cooling is efficient. With the increased cooling effectiveness of multiphase cooling, a tetrode, such as the 4CM2500KG, can be cooled with approximately one third the volumetric water flow that an equivalent standard water cooled tube version would require.

From a maintenance point of view, multiphase cooling systems should be supplied with very pure water and as little dissolved air and oxygen in the water as possible. Since the anode surface is essentially acting as a boiler, it will extract out all solids in the water, leaving them as deposits on the anode.

Similarly, air and oxygen in the water will cause oxidation of the anode's surface. Both of these mechanisms can cause overheating of the tube and should be avoided.

CAUTION: Multiphase cooled tubes have special anode designs to promote conversion of water to steam and then rapidly removing the steam. Do not try to operate tubes designed for water or pure vapor phase cooling as multiphase cooled tubes. This will result in tube failure.

USEFUL CONVERSION FACTORS

ENERGY

BTU	= energy required **to** raise one pound of water one degree fahrenheit
CALORIE	= energy required to raise one gram of water one degree centigrade
KILOGRAM-CALORIE	= 1000 calories
1 kW	= 3413 Btu/hr
	= 57 Btu/min
	= 860 kg-calories/hr
	= 14.34 kg-calories/min
1 Btu	= 252 calories

BOILING

Latent heat of vaporization (water at atmospheric pressure)	= 540 calories/gram
	= 970 Btu/lb
1 kW dissipation	= 3.53 pounds H_2O/hr at 100°C transformed into steam at 100’C
	= 0.42 gallons/hr
1 cubic foot water	=62.4 pounds of water
	= 7.48 gallons of water
	=1600 cubic feet of steam

GENERAL

C	$= \frac{5}{9}(F-32)$
F	$= \frac{9}{5}(C+32)$
1 inch H_20	= 0.036 psi
	= 0.58 oz/in2
1 inch Hg	= 0.49 psi

Figure 88. Useful conversion factors.

6.10.10 Conduction Cooling

As power tubes become more compact, the problems of removing the heat increase. All of the previously mentioned cooling techniques can and have been used with compact equipment. There are certain applications where conduction cooling is the preferred technique. A typical application of a conduction cooled tube would be in airborne equipment. The skin of the aircraft, or other vehicle, may be used as an infinite heat sink. No pressurization is required as is for convection and forced air cooling. No liquid and associated circulating system is required. Another application is in shipborne equipment. The hull of the ship is a perfect heat sink.

Quite often in mobile and fixed applications it is desirable to conduct all heat in the equipment to one cold plate which can be air or liquid cooled.

Large tubes can use liquid cooled conduction clamps. This technique will permit the replacement of the tube without exposure of the liquid system to the atmosphere.

In conduction cooled power tubes, the cooling system is an integral part of the electrical circuit. The thermal link between the anode and the heat sink can, in certain applications, add to the output capacitance. The method of contacting the base of the tube must satisfy both the electrical and heat transfer requirements.

6.11 TUBE LIFE

6.11.1 Maximum Tube Ratings

The technical data sheet for each tube type gives the basic maximum ratings for each class of service. The data sheet also gives references to the type of cooling required and how much. The maximum temperature permissible for reasonable life is also specified. Careful observance of the information on the data sheet will avoid damage to the tube and shortening of its useful life.

The typical life expectancy will depend upon a great many factors. In general, operation below the maximum ratings will increase the life expectancy of the tube. This is especially true with reduction in the anode dissipation of the tube.

If tubes are to be used in pulse service with short pulses and appreciable off-time between pulses, the tube ratings are quite different.

A very large factor in tube life is the temperature of the thoriated-tungsten cathode. The equipment manufacturer and the end user of the equipment have more control over tube life through proper adjustment of filament voltage (filament power) than is generally realized. This is true because tube ratings and equipment designs are conservative in peak cathode emission required of the tube compared with peak cathode emission available at nominal rated filament voltage.

It is good practice to determine, in the field for each particular combination of equipment and operating power level, the nominal filament voltage for best life. This is best done in the field by measuring some important parameter of performance such as anode current, power output, or distortion, while filament voltage on the power tube is reduced. At some point in filament voltage there will be a noticeable reduction in anode current, or power output, or an increase in distortion. Safe operation may be at a filament voltage slightly higher than that point at which performance appeared to deteriorate. A recheck should be made in 12 to 24 hours to make certain the emission is stable.

The thoriated-tungsten filament or cathode is processed in a hydrocarbon atmosphere to form a deep layer of di-tungsten carbide on the surface. Stable emission is not possible without the carbide. If the carbide layer is too deep, the filament becomes too brittle to withstand shipping and handling. The end of useful life for this type of filament occurs when most of the carbon has evaporated or combined with residual gas, depleting the carbide surface layer. During this process, the value of filament current increases approximately 5% above the intial new-tube value.

Theoretically a 3% increase in filament voltage will result in a 20º Kelvin increase in temperature, a 20% increase in peak emission, and a 50% decrease in life due to carbon loss. This, of course, works the other way, too. For a small decrease in temperature and peak emission, life of the carbide layer and hence tube life can be increased by a substantial percentage. Peak emission as meant here is the emission obtained in the test for emission described in the Test Specification. This is normally many times the peak emission required in communication service.

EIMAC Applications Bulletin AB-18 covers this subject in detail. See www.eimac.com under Applications.

6.11.2 VHF and UHF Life Considerations

A tube designed for VHF and UHF work must be very small if practical resonant circuits are to be built around them. Furthermore, these tubes operate less efficiently and have much greater incidental losses than at a lower frequency. For these reasons, the power which must be dissipated from the electrodes and tube envelope seals is much greater per unit of area than for tubes designed solely for low frequency.

If the tubes are to become part of a UHF line circuit or cavity UHF circuit, the inductance associated with the electrode supports and leads must be reduced to a very small value. In the case of the 4CPX250K, 4CX250B and 3CX10,000U7 type structures, some of the electrode leads and supports take the form of large surfaces, conical or cylindrical in shape, and extremely short. This means that the amount of heat conducted out through the metal-to-ceramic seals is greatly increased. It also means that the terminal connections of the tube are large surfaces with relatively thin walls.

The mechanical layout of sockets, connections and circuits close to the tube must allow ample cooling air to be blown against the tube seals and surfaces. Also, ample contacting surface must be provided to carry heavy radio frequency charging currents. Since these two requirements may tend to conflict, considerable thought must be given to an adequate layout.

6.11.3 Connectors

Where the tube terminals are large cylindrical surfaces, the contacting portions of the socket are either spring collets or a multiplicity of spring fingers. Usually these multiple contacting surfaces are made of beryllium copper to preserve the spring tension at the relatively high temperatures present on the tube terminals, and are silver plated to reduce RF resistance.

Rigid clamping connectors should be avoided even though the radius of the curvature seems to be close to that of the cylindrical contacting surface of the tube. It has been found that such rigid clamping connectors will distort the tube terminal and fracture the adjacent seal. Similarly set screw connecting devices are questionable on large cylindrical tube terminals unless they act to distribute the pressure uniformly and without any distorting effects.

If the connectors fail to provide multiple contacts to the cylindrical tube seals, concentration of RF charging current will result and the local overheating may be destructive. Once the connector loses its spring action the heating is aggravated and damage to the tube is very apt to occur. All tube connectors should be inspected and serviced regularly to be sure that uniform, good contact to the tube results.

It is never advisable to drill holes in any part of the tube structure to provide contact. Many of the metal parts are only 10 to 15 thousandths of an inch thick.

6.11.4 Backheating by Electrons

Another action involving the motion of electrons within the tube is present at VHF and UHF and has been commonly referred to as backheating of the cathode. Due to the fact that the time of flight of the electrons (also called transit time) from the cathode through the grid structure to the anode becomes an appreciable part of the cycle, the electrons can be stopped in flight and turned back by the rapidly changing grid voltage. Under these conditions the electrons are turned back or deflected from their normal paths and given excess energy with which the electrons bombard the cathode and other portions of the tube structure. This effect can be greatly aggravated by the choice of operating conditions to the extent that very destructive effects occur. The tube can even be destroyed within a few minutes under severe conditions.

Fortunately, the conditions which tend to minimize this back bombardment by electrons are the same as those giving minimum driving voltage as discussed under “VHF Operating Conditions.” The tendency for electrons to be turned back in flight is reduced by the use of the lowest possible RF grid voltage on the tube. This is obtained by using the lowest possible dc grid bias. In tetrodes this effect is inherently much lower because of the action of the dc accelerating the electrons toward the anode, and also inherently permits the use of much smaller grid voltages. Consequently, under favorable conditions the number of electrons turned back to heat the cathode and tube structure can be kept to a practical low level. In addition to the use of low dc grid bias, a high screen voltage is desirable.

At the same time, the anode circuit should always operate with heavy loading (low external anode impedance) so that the minimum instantaneous value of anode voltage shall stay sufficiently positive to continue accelerating electrons to the anode. For this reason, best life is had when the tetrode amplifier is heavily loaded as indicated by having small values of dc screen and dc control grid current.

NEVER OPERATE WITH LIGHT ANODE LOADING. If the anode load is removed so that the minimum instantaneous anode voltage tends to fall to values around cathode potential (as it must do when the loading is removed completely and excitation is present), the number of electrons turned back can be completely destructive to the tube. It has been found that under conditions of “no loading” the electron bombardment and increased electric field heating of the insulating portion of the tube is often sufficient to cause a suck-in of the glass, or even cause cracking of a ceramic envelope. Automatic protection should be installed to remove all voltages from the tube when the anode circuit loading becomes too light for the amount of excitation applied.

It should be noted that parasitic oscillations are seldom loaded heavily, as indicated by the high grid currents often had during such self-oscillation. Thus, excessive RF anode voltages are developed which, at VHF, can be damaging in the same manner as unloaded operation on a VHF fundamental frequency. Should such unloaded VHF parasitic oscillation be present simultaneously with apparently satisfactory operation on the fundamentals, unexplained reduction of life may result.

Occasionally, also, an output line circuit can resonate simultaneously to a harmonic frequency as well as to the fundamental frequency. The higher resonant modes of practical line circuits are not normally harmonically related, but sometimes the tuning curve of a mode will cross the fundamental tuning curve and at that point the circuit will build up resonant voltages at both the harmonic frequency and fundamental frequency. The harmonic resonance is usually lightly loaded and the damaging action is similar to that of lightly loaded parasitic or fundamental operation. Again, the operation of the tube and circuit on the fundamental may appear normal, but with lower than expected efficiency, damaging action can occur to some degree.

In addition to operating the tube with minimum bias, high screen voltage, and heavy loading on the anode circuit, some degree of compensation for the remaining backheating of the cathode may be required. This can be accomplished by lowering the filament voltage or heater voltage until the cathode operates at normal temperature. It has been found with tetrodes and pentodes that by taking precautions necessary to minimize back-bombardment by electrons the compensation for backheating of the cathode is not large and may often be neglected.

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