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Chapter

8

Cooling Considerations

8.1 Introduction

Adequate cooling of the tube envelope and seals is one of the principal factors affecting vacuum tube life [1]. Deteriorating effects increase directly with the temperature of the tube envelope and ceramic/metal seals. Inadequate cooling is almost certain to invite premature failure of the device.

Tubes operated at VHF and above are inherently subjected to greater heating action than tubes operated at lower frequencies. This results directly from the following:

- The flow of larger RF charging currents into the tube capacitances at higher frequencies
- Increased dielectric losses at higher frequencies
- The tendency of electrons to bombard parts of the tube structure other than the normal elements as the operating frequency is increased

Greater cooling, therefore, is required at higher frequencies. The technical data sheet for a given tube type specifies the maximum allowable operating temperature. For forced-air- and water-cooled tubes, the recommended amount of air or water is also specified in the data sheet. Both the temperature and quantity of coolant should be measured to be certain that cooling is adequate.

8.1.1 Thermal Properties

In the commonly used model for materials, heat is a form of energy associated with the position and motion of the molecules, atoms, and ions of the material [2]. The position is analogous with the state of the material and is *potential energy*, while the motion of the molecules, atoms and ions is *kinetic energy*. Heat added to a material makes it hotter, and heat withdrawn from a material makes it cooler. Heat energy is measured in *calories* (cal), *British Thermal Units* (Btu), or *joules*. A calorie is the amount of energy required to raise the temperature of one gram of water one degree Celsius (14.5 to 15.5 ºC). A Btu is the unit of energy necessary to raise the temperature of one pound of water by one degree Fahrenheit. A joule is an equivalent amount of energy equal to the work done when a force of one newton acts through a distance of one meter.

Temperature is a measure of the average kinetic energy of a substance. It can also be considered a relative measure of the difference of the heat content between bodies.

Heat capacity is defined as the amount of heat energy required to raise the temperature of one mole or atom of a material by one ºC without changing the state of the material. Thus, it is the ratio of the change in heat energy of a unit mass of a substance to its change in temperature. The heat capacity, often referred to as *thermal capacity*, is a characteristic of a material and is measured in cal/gram per ºC or Btu/lb per ºF.

Specific heat is the ratio of the heat capacity of a material to the heat capacity of a reference material, usually water. Because the heat capacity of water is one Btu/lb and one cal/gram, the specific heat is numerically equal to the heat capacity.

Heat transfers through a material by conduction resulting when the energy of atomic and molecular vibrations is passed to atoms and molecules with lower energy. As heat is added to a substance, the kinetic energy of the lattice atoms and molecules increases. This, in turn, causes an expansion of the material that is proportional to the temperature change, over normal temperature ranges. If a material is restrained from expanding or contracting during heating and cooling, internal stress is established in the material.

8.1.2 Heal Transfer Mechanisms

The process of heat transfer from one point or medium to another is a result of temperature differences between the two. Thermal energy may be transferred by any of three basic modes:

- Conduction
- Convection
- Radiation

A related mode is the convection process associated with the change of phase of a fluid, such as condensation or boiling. A vacuum tube amplifier or oscillator may use several of these mechanisms to maintain the operating temperature of the device within specified limits.

Conduction

Heat transfer by conduction in solid materials occurs whenever a hotter region with more rapidly vibrating molecules transfers a portion of its energy to a cooler region with less rapidly vibrating molecules. Conductive heat transfer is the most common form of thermal exchange in electronic equipment. Thermal conductivity for solid materials used in electronic equipment spans a wide range of values, from excellent (high conductivity) to poor (low conductivity). Generally speaking, metals are the best conductors of heat, whereas insulators are the poorest. Table 8.1 lists the thermal conductivity of materials commonly used in the construction (and environment) of

Table 8.1 Thermal Conductivity of Common Materials

Material	Btu/(h·ft·°F)	W/(m·°C)
Silver	242	419
Copper	228	395
Gold	172	298
Beryllia	140	242
Phosphor bronze	30	52
Glass (borosilicate)	0.67	1.67
Mylar	0.11	0.19
Air	0.015	0.026

Table 8.2 Relative Thermal Conductivity of Various Materials As a Percentage of the Thermal Conductivity of Copper

Material	Relative Conductivity
Silver	105
Copper	100
Berlox high-purity BeO	62
Aluminum	55
Beryllium	39
Molybdenum	39
Steel	9.1
High-purity alumina	7.7
Steatite	0.9
Mica	0.18
Phenolics, epoxies	0.13
Fluorocarbons	0.05

power vacuum tubes. Table 8.2 compares the thermal conductivity of various substances as a percentage of the thermal conductivity of copper.

With regard to vacuum tube devices, conduction is just one of the cooling mechanisms involved in maintaining element temperatures within specified limits. At high power levels, there is always a secondary mechanism that works to cool the device. For example, heat generated within the tube elements is carried to the cooling surfaces of the device by conduction. Convection or radiation then is used to remove heat from the tube itself.

Thermal conduction has been used successfully to cool vacuum tubes through direct connection of the anode to an external heat sink, but only at low power levels [1].

Convection

Heat transfer by natural convection occurs as a result of a change in the density of a fluid (including air), which causes fluid motion. Convective heat transfer between a heated surface and the surrounding fluid is always accompanied by a mixing of fluid adjacent to the surface. Power vacuum tube devices relying on convective cooling invariably utilize forced air or water passing through a heat-transfer element, typically the anode in a grid tube or the collector in a microwave tube [1]. This *forced convection* provides for a convenient and relatively simple cooling system. In such an arrangement, the temperature gradient is confined to a thin layer of fluid adjacent to the surface so that the heat flows through a relatively thin *boundary layer*. In the main stream outside this layer, isothermal conditions exist.

Radiation

Cooling by radiation is a function of the transfer of energy by electromagnetic wave propagation. The wavelengths between 0.1 and 100 m are referred to as *thermal radiation wavelengths*. The ability of a body to radiate thermal energy at any particular wavelength is a function of the body temperature and the characteristics of the surface of the radiating material. Figure 8.1 charts the ability to radiate energy for an ideal radiator, a *blackbody*, which, by definition, radiates the maximum amount of energy at any wavelength. Materials that act as perfect radiators are rare. Most materials radiate energy at a fraction of the maximum possible value. The ratio of the energy radiated by a given material to that emitted by a blackbody at the same temperature is termed *emissivity*. Table 8.3 lists the emissivity of various common materials.

8.1.3 The Physics of Boiling Water

The *Nukiyama curve* shown in Figure 8.2 charts the heat-transfer capability (measured in watts per square centimeter) of a heated surface, submerged in water at various temperatures [1]. The first portion of the curve—*zone A*—indicates that from 100 to about 108°C, heat transfer is a linear function of the temperature differential between the hot surface and the water, reaching a maximum of about 5 W/cm^2 at 108°C. This linear area is known as the *convection cooling zone*. Boiling takes place in the heated water at some point away from the surface.

From 108 to 125°C—*zone B*—heat transfer increases as the fourth power of ΔT until, at 125°C, it reaches 135 W/cm^2. This zone is characterized by *nucleate boiling*; that is, individual bubbles of vapor are formed at the hot surface, break away, and travel upward through the water to the atmosphere.

Above 125°C, an unstable portion of the Nukiyama curve is observed, where increasing the temperature of the heated surface actually reduces the unit thermal conductivity. At this area—*zone C*—the vapor partially insulates the heated surface from the water until a temperature of approximately 225°C is reached on the hot surface. At this point—called the *Leidenfrost point*—the surface becomes completely covered with a sheath of vapor, and all heat transfer is accomplished through this vapor cover. Thermal conductivity of only 30 W/cm^2 is realized at this region.

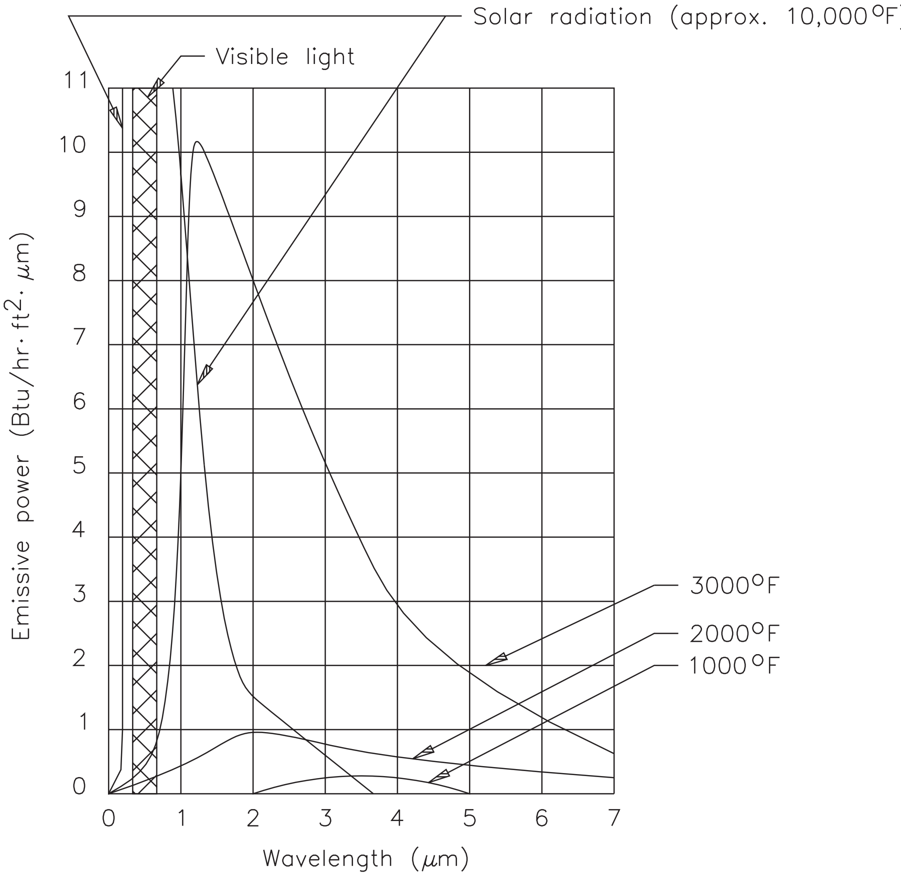

Figure 8.1 Blackbody energy distribution characteristics.

Table 8.3 Emissivity Characteristics of Common Materials at 80°F

Surface Type	Finish	Emissivity
Metal	Copper (polished)	0.018
Metal	Nickel	0.21
Metal	Silver	0.10
Metal	Gold	0.04–0.23
Glass	Smooth	0.9–0.95
Ceramic	Cermet[1]	0.58
[1] Ceramic containing sintered metal		

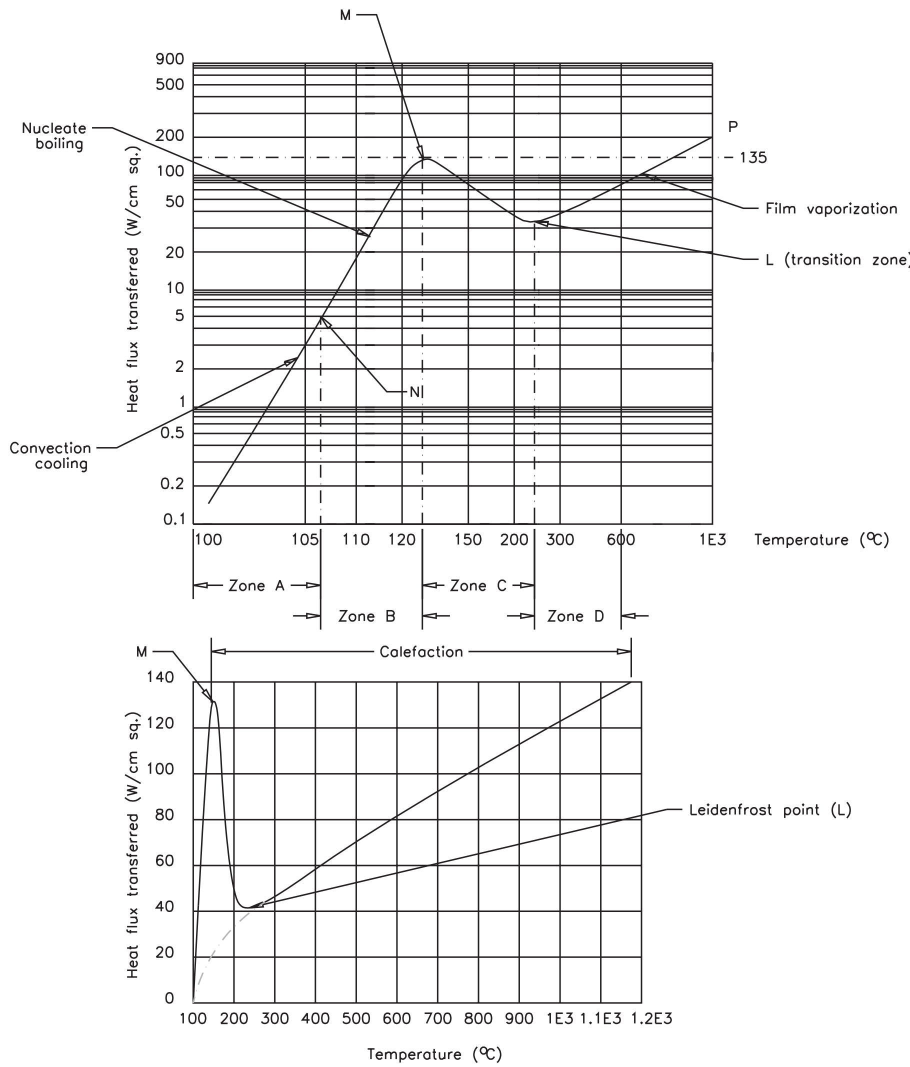

Figure 8.2 Nukiyama heat-transfer curves: (*a*) logarithmic, (*b*) linear.

From the Leidenfrost point on through *zone D*—the *film vaporization zone*—heat transfer increases with temperature until at about 1000°C the value of 135 W/cm^2 again is reached.

The linear plot of the Nukiyama curve indicates that zones *A* and *B* are relatively narrow areas and that a heated surface with unlimited heat capacity will tend to pass from zone *A* to zone *D* in a short time. This irreversible superheating is known as *calefaction*. For a cylindrical vacuum tube anode, the passing into total calefaction would not be tolerated, because any unit heat-transfer density above 135 W/cm^2 would result in temperatures above 1000°C, well above the safe limits of the tube.

These properties dictate many of the physical parameters of water- and vapor-cooled power vacuum tubes. For a given dissipation, the anode structure that comes in contact with the coolant must be sufficient to keep the tube operating within the desired cooling zone of the Nukiyama curve and, in any event, at less than 135 W/cm^2 dissipation on the anode structure.

8.2 Application of Cooling Principles

Excessive dissipation is perhaps the single greatest cause of catastrophic failure in a power tube [1]. PA tubes used in communications, industrial, and research applications can be cooled using one of three methods: forced-air, liquid, and vapor-phase cooling (discussed in Chapter 3). Forced-air cooling is the simplest and most common method used.

The critical points of almost every PA tube type are the metal-to-ceramic junctions or seals. At temperatures below 250°C these seals remain secure, but above that temperature, the bonding in the seal may begin to disintegrate. Warping of grid structures also may occur at temperatures above the maximum operating level of the device. The result of prolonged overheating is shortened tube life or catastrophic failure. Several precautions usually are taken to prevent damage to tube seals under normal operating conditions. Air directors or sections of tubing may be used to provide spot cooling at critical surface areas of the device. Airflow sensors typically prevent operation of the RF system in the event of a cooling system failure.

Temperature control is important for vacuum tube operation because the properties of many of the materials used to build a tube change with increasing temperature. In some applications, these changes are insignificant. In others, however, such changes can result in detrimental effects, leading to—in the worst case—catastrophic failure. Table 8.4 details the variation of electrical and thermal properties with temperature for various substances.

8.2.1 Forced-Air Cooling Systems

Air cooling is the simplest and most common method of removing waste heat from a vacuum tube device [1]. The basic configuration is illustrated in Figure 8.3. The normal flow of cooling air is upward, making it 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 at 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 to cool the envelope, and enters the output circuit compartment.

The output compartment is provided with a mesh-covered opening that permits the air to vent out readily. High-power tubes typically include a chimney to direct airflow, as shown in Figure 8.4. For a forced-air design, a suitable fan or blower is used to pressurize the compartment below the tube. No holes should be provided for the passage of

Table 8.4 Variation of Electrical and Thermal Properties of Common Insulators As a Function of Temperature

Parameters		20°C	120°C	260°C	400°C	538°C
Thermal conductivity[1]	99.5% BeO	140	120	65	50	40
	99.5% Al_2O_3	20	17	12	7.5	6
	95.0% Al_2O_3	13.5				
	Glass	0.3				
Power dissipation[2]	BeO	2.4	2.1	1.1	0.9	0.7
Electrical resistivity[3]	BeO	10^{16}	10^{14}	5×10^{12}	10^{12}	10^{11}
	Al_2O_3	10^{14}	10^{14}	10^{12}	10^{12}	10^{11}
	Glass	10^{12}	10^{10}	10^{8}	10^{6}	
Dielectric constant[4]	BeO	6.57	6.64	6.75	6.90	7.05
	Al_2O_3	9.4	9.5	9.6	9.7	9.8
Loss tangent[4]	BeO	0.00044	0.00040	0.00040	0.00049	0.00080

[1] Heat transfer in Btu/ft^2/hr/°F
[2] Dissipation in W/cm/°C
[3] Resistivity in Ω-cm
[4] At 8.5 GHz

air from the lower to the upper compartment other than the passages through the socket and tube base. A certain amount of pressure must be built up to force the proper amount of air through the socket to cool the anode.

Attention must be given to airflow efficiency and turbulence in the design of a cooling system. Consider the case shown in Figure 8.5. Improper layout has resulted in inefficient movement of air because of circulating thermal currents. Anode cooling will be insufficient in this case.

The cooling arrangements illustrated in Figures 8.3 and 8.4 provide for the uniform passage of cooling air over the tube base and anode. An arrangement that forces cooling air transversely across the tube base and/or anode will not provide the same cooling effectiveness and may result in hot spots on the device.

In many cases, packaged air system sockets and chimneys are designed specifically for a tube or family of tube types. The technical data sheet specifies the recommended socketing for adequate cooling. The tube data sheet also will specify 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 device consists of a U-shaped glass tube partially filled with water, as shown in Figure 8.6.

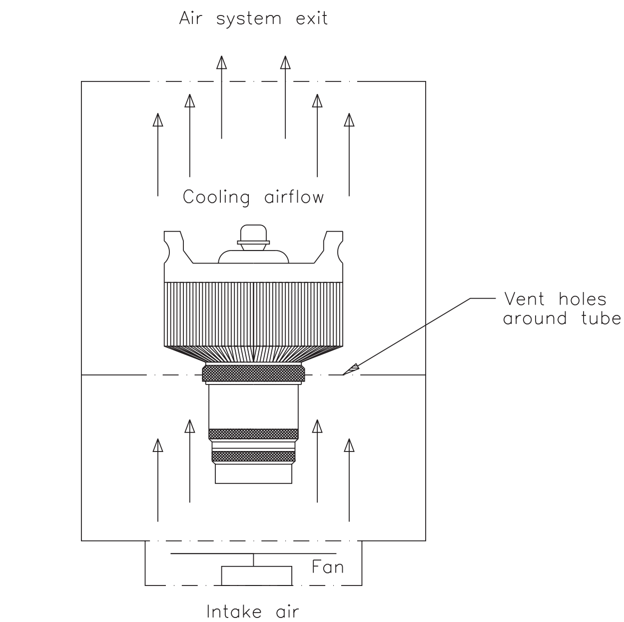

Figure 8.3 Cooling system design for a power grid tube.

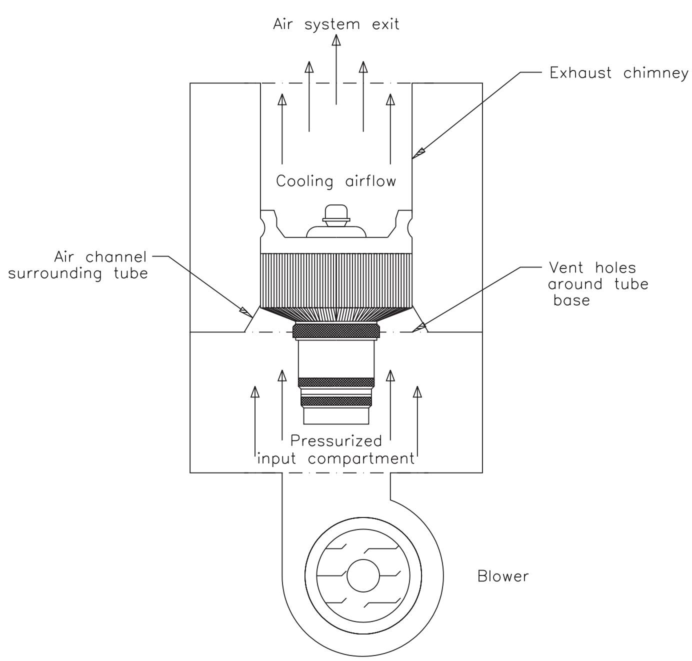

Figure 8.4 The use of a chimney to improve cooling of a power grid tube.

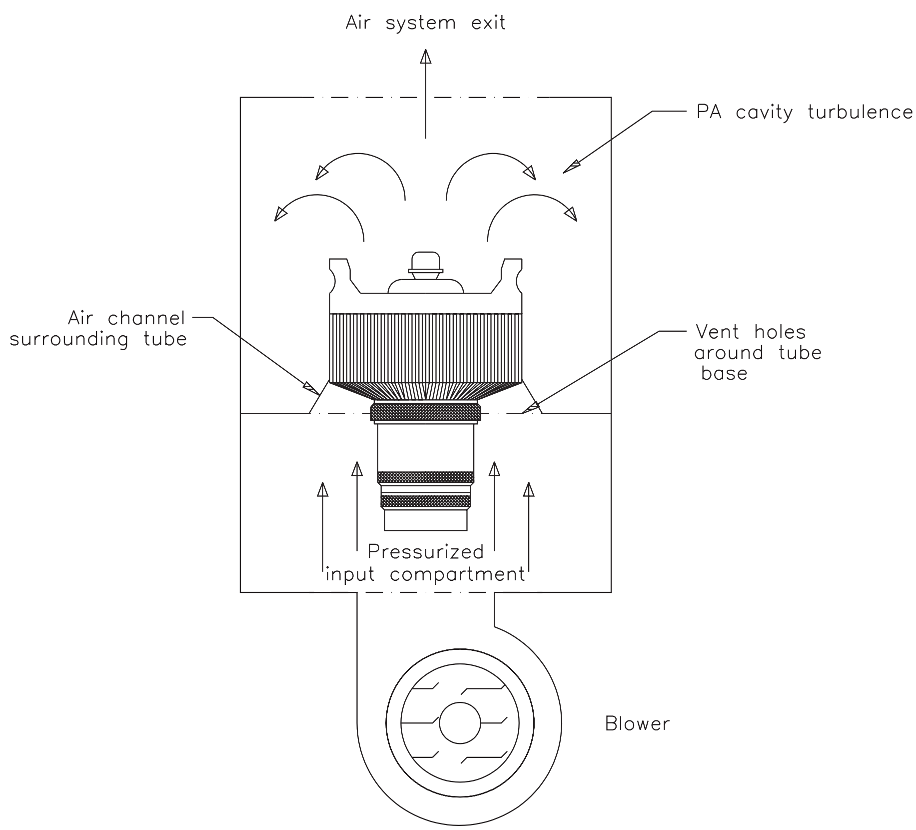

Figure 8.5 A poorly designed cooling system in which circulating air in the output compartment reduces the effectiveness of the heat-removal system.

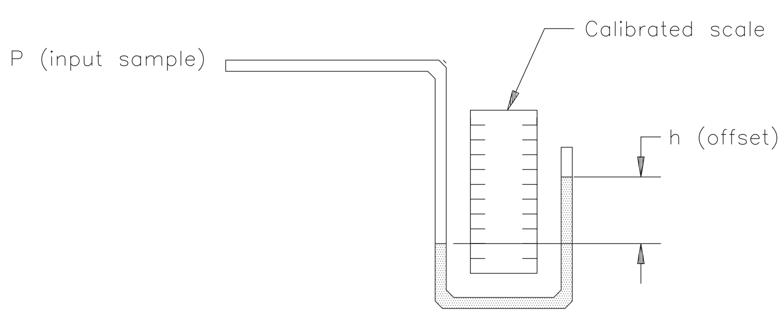

Figure 8.6 A manometer, used to measure air pressure.

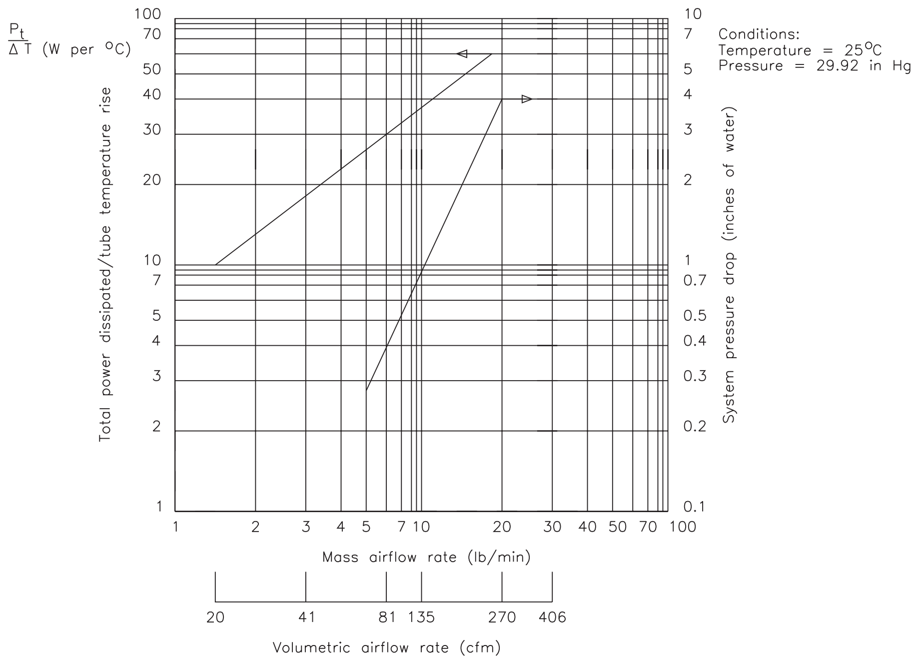

Figure 8.7 Cooling airflow requirements for a power grid tube. (*Data courtesy of Varian.*)

Cooling Airflow Data

Power tube manufacturers typically outline minimum cooling airflow requirements for large external-anode tubes in the form of one or more charts [1]. Figure 8.7 plots $P_t/\Delta T$ as a function of A_m, where P_t = total power dissipated in watts, ΔT = tube temperature rise in degrees Celsius, and A_m = mass airflow rate in pounds of air per minute. This type of graph is used in calculating the cooling requirements of a vacuum tube device. The graph applies to a specified tube and socket-chimney combination; furthermore, the direction of airflow is specified. When reverse airflow (from anode to base) is used, the cooling requirements are sharply increased because the air applied to the base seals already will have been heated by its passage through the anode cooler, losing much of its cooling effectiveness.

To use the type of graph shown in Figure 8.7, first determine the minimum cooling requirements using the following steps:

1. Calculate the total power dissipated (P_t) by adding all of the power dissipated by the tube during operation in a given installation. This value includes plate and fila-

ment dissipations, plus maximum anticipated grid and screen dissipations (as applicable).

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

3. To convert the mass airflow rate M (pounds per minute) to volumetric airflow rate Q (cubic feet per minute) at 25°C and at sea level, divide the mass airflow rate by the density of air at 25°C and 29.9 in mercury.

4. The curve on the right side of the graph is the pressure drop (ΔP) in inches of water across the tube and its specified socket-chimney combination. This value is valid at 25°C at sea level only.

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 the laboratory standard density (0.074 lb/ft^3; 25°C at sea level) to the density at the new socket-inlet condition.

A shorter method may be used to approximately 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 by the appropriate correction factors listed in Table 8.5.

Figure 8.8 is a graph of the combined correction factors that can be applied to the 25°C sea-level information for land-based installations located at elevations up to 10,000 ft, and for socket-inlet air temperatures between 10 and 50°C. Figure 8.9 provides a method to convert the mass airflow rate in pounds per minute into volumetric airflow rate (cfm) at 25°C and sea level.

Good engineering practice must be used when applying altitude and temperature corrections to the 25°C sea-level cooling requirement for airborne applications. 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 the installation design (compressed, ram, static, or recirculating air in a pressurized heat exchanger).

Blower Selection

In the previous section, a method of determining minimum air cooling requirements for external-anode tubes was described, pertaining to any altitude and air temperature [1]. Because most blower manufacturers furnish catalog data on their products in the form of volumetric airflow (Q, cfm) vs. operating back pressure (ΔP, inches of water) for sea level conditions only, the information gained from the foregoing procedure cannot be compared directly with data furnished by manufacturers for the purpose of selecting the proper device. The following method is recommended for use in selecting a blower for applications above sea level from existing blower catalog data:

Table 8.5 Correction Factors for *Q* and Δ*P*

Socket-Inlet Air Temperature (°C)	Q and Δ*P* 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[1]	**Altitude (ft)**	**Q and Δ*P* Correction Factor**
29.92	0	1.00
24.90	5000	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

[1] Pressure in inches of mercury

1. Determine the *Q* and Δ*P* requirements for the tube socket-chimney combination for an ambient air temperature of 25°C at sea level. Include the estimated Δ*P* of ducting and filters in the system.

2. Determine the corrected *Q* and Δ*P* system requirements for the actual inlet temperature and altitude conditions by multiplying by the correction factor shown in Figure 8.7.

3. Multiply the Δ*P*—but not the *Q*—requirement by the correction factor cited in step 2.

4. Use the corrected *Q* factor and doubly-corrected Δ*P* value 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 at high-altitude conditions.

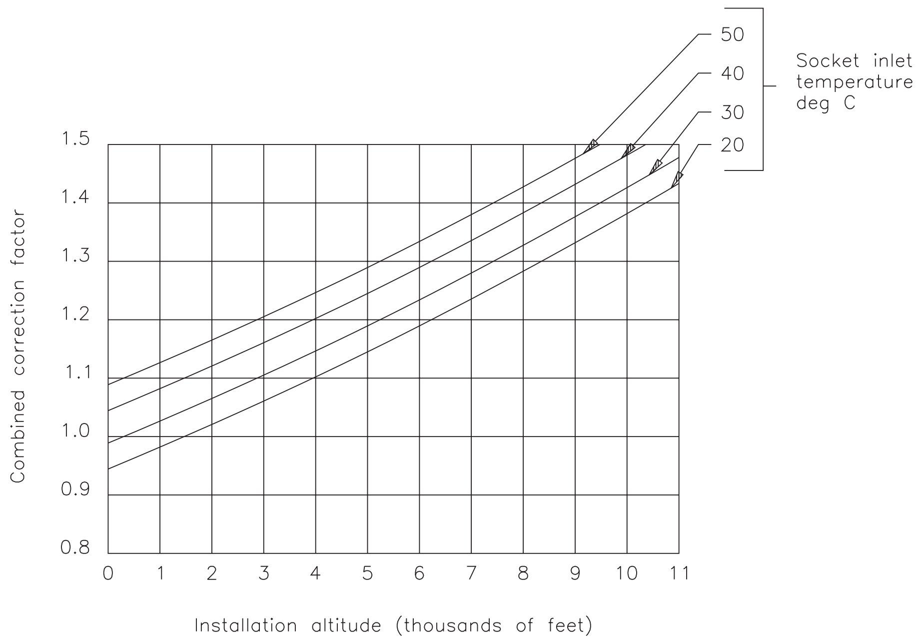

Figure 8.8 Combined correction factors for land-based tube applications.

8.2.2 Water Cooling

A water-cooled tube depends upon an adequate flow of fluid to remove heat from the device and transport it to an external heat sink [1]. The recommended flow as specified in the technical data sheet should be maintained at all times when the tube is in operation. Inadequate water flow at high temperature may cause the formation of steam bubbles at the anode surface where the water is in direct contact with the anode. This condition can contribute to premature tube failure.

Circulating water can remove about 1.0 kW/cm^2 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. The water then is passed through a heat exchanger where it is cooled to 30 to 40°C before being pumped over the tube anode again.

Cooling System Design

A liquid cooling system consists of the following principal components:

- A source of coolant
- Circulation pump

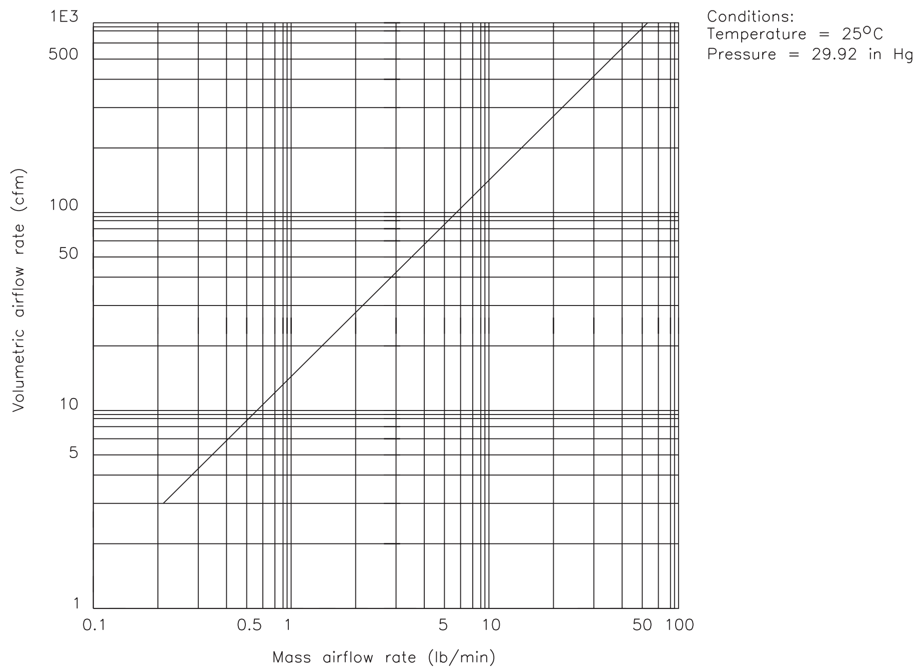

Figure 8.9 Conversion of mass airflow rate to volumetric airflow rate.

- Heat exchanger
- Coolant purification loop
- Various connection pipes, valves, and gauges
- Flow interlocking devices (required to ensure coolant flow anytime the equipment is energized)

Such a system is shown schematically in Figure 8.10. In most cases the liquid coolant will be water, but if there is a danger of freezing, it will be necessary to use an antifreeze solution such as ethylene glycol. In these cases, coolant flow must be increased or plate dissipation reduced to compensate for the poorer heat capacity of the ethylene glycol solution. A mixture of 60 percent ethylene glycol to 40 percent water by weight will be about 75 percent as efficient as pure water at 25°C. Regardless of the choice of liquid, the system volume must be maintained above the minimum required to ensure proper cooling of the vacuum tube(s).

The main circulation pump must be of sufficient size to ensure necessary flow and pressure as specified on the tube data sheet. Care must be taken when connecting the coolant lines to the tube to be certain that flow is in the direction specified. Improper direction of flow may result in inadequate cooling as well as excessive pressure and possi-

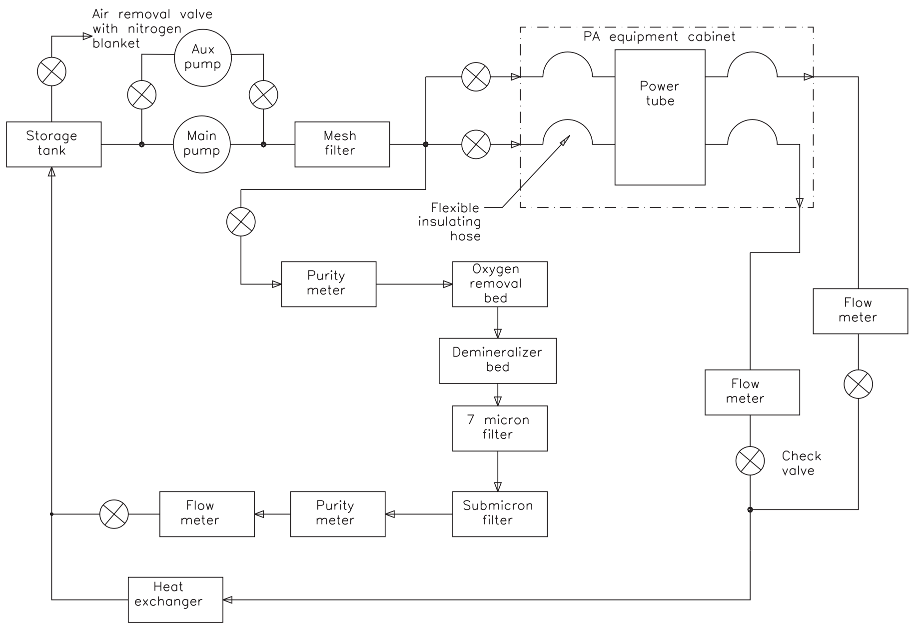

Figure 8.10 Functional schematic of a water cooling system for a high-power amplifier or oscillator.

ble mechanical deformation of the anode. Precautions should be taken during system design to protect against water *hammering* of the anode. A filter screen of at least 60 mesh usually is installed in the pump outlet line to trap any circulating debris that might clog coolant passages within the tube.

The heat exchanger system is sized to maintain the outlet temperature such that the outlet water from the tube at full plate dissipation does not exceed 70°C. Filament or grid coolant courses may be connected in parallel or series with the main supply as long as the maximum outlet temperature is not exceeded.

Valves and pressure meters are installed on the inlet lines to the tube to permit adjustment of flow and measurement of pressure drop, respectively. A pressure meter and check valve are employed in the outlet line. In addition, a flow meter—sized in accordance with the tube data sheet—and a thermometer are included in the outlet line of each coolant course. These flow meters are equipped with automatic interlock switches, wired into the system electrical controls, so that the tube will be completely deenergized in the event of a loss of coolant flow in any one of the coolant passages. In some tubes, filament power alone is sufficient to damage the tube structure in the absence of proper water flow.

The lines connecting the plumbing system to the inlet and outlet ports of the tube are made of a flexible insulating material configured so as to avoid excessive strain on the tube flanges. Polypropylene tubing is the best choice for this service, but chlorinated polyvinyl chloride (CPVC) pipe, which is stronger, also is acceptable. Reinforced poly-

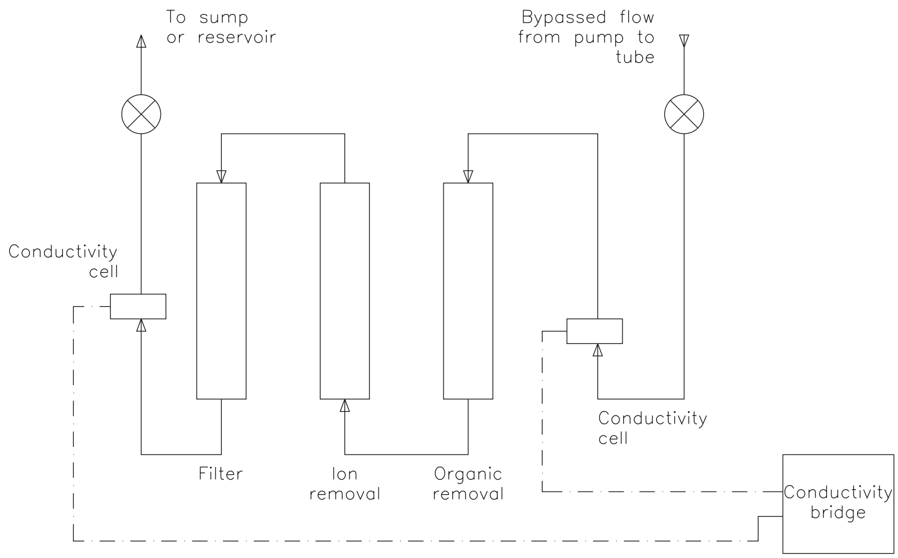

Figure 8.11 Typical configuration of a water purification loop.

propylene, such as *Nylobraid*, is expensive, but excellent in this application. The coolant lines must be of sufficient length to keep electrical leakage below 4 mA at full operating power.

The hoses are coiled or otherwise supported so that they do not contact each other or any conducting surface between the high-voltage end and ground. Conducting hose *barbs*, connected to ground, are provided at the low-potential end so that the insulating column of water is broken and grounded at the point where it exits the equipment cabinet.

All metallic components within the water system, including the pump, must be of copper, stainless steel, or unleaded brass or bronze; copper or stainless steel is preferred. If brass or bronze is used, some zinc may be leached out of the metal into the system. Any other material, such as iron or cold rolled steel, will grossly contaminate the water.

Even if the cooling system is constructed using the recommended materials, and is filled with distilled or deionized water, the solubility of the metals, carbon dioxide, and free oxygen in the water make the use of a coolant purification (*regeneration*) loop essential. The integration of the purification loop into the overall cooling system is shown in Figure 8.10. The regeneration loop typically taps 5 to 10 percent of the total cooling system capacity, circulating it through oxygen scavenging and deionization beds, and submicron filters before returning it into the main system. Theoretically, such a purification loop can process water to 18 MΩ-cm resistivity at 25ºC. In practice, resistivity will be somewhat below this value.

Figure 8.11 shows a typical purification loop configuration. Packaged systems such as the one illustrated are available from a number of manufacturers. In general, such

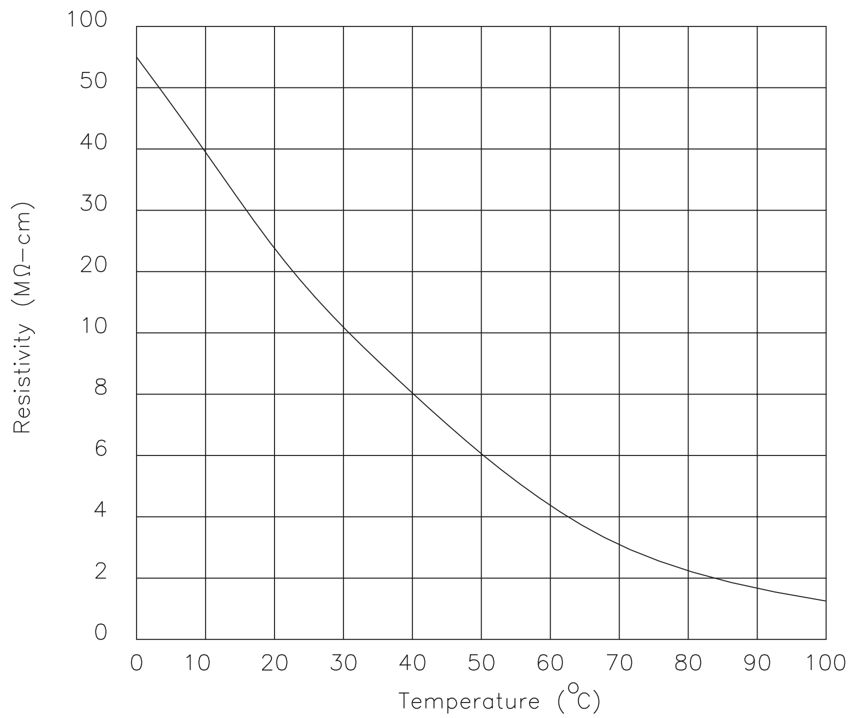

Figure 8.12 The effect of temperature on the resistivity of ultrapure water.

systems consist of replaceable cartridges that perform the filtering, ion exchange, and organic-solid-removal functions. The system usually will include flow and pressure gauges and valves, and conductivity cells for continuous evaluation of the condition of the water and filters.

Water Purity and Resistivity

The purity of the cooling water is an important operating parameter for any water-cooled amplifier or oscillator. The specific resistivity must be maintained at 1 MΩ-cm minimum at 25ºC. Distilled or deionized water should be used and the purity and flow protection periodically checked to ensure against 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 that might clog coolant passages within the tube.

After normal operation for an extended period, the cooling system should be capable of holding 3 to 4 MΩ-cm until the filter beds become contaminated and must be replaced. The need to replace the filter bed resins is indicated when the purification loop output water falls below 5 MΩ-cm. Although the resistivity measurement is not a test for free oxygen in the coolant, the oxygen filter bed always should be replaced when the deionizing bed is replaced.

The resistivity of the coolant also is affected by the temperature of the water. The temperature-dependence of the resistivity of pure water is charted in Figure 8.12.

It is recommended that the coolant water be circulated at all times. This procedure provides the following benefits:

- Maintains high resistivity
- Reduces bacteria growth
- Minimizes oxidation resulting from coolant stagnation

If it is undesirable to circulate the coolant at the regular rate when the tube is deenergized, a secondary circulating pump can be used to move the coolant at a lower rate to purge any air that might enter the system and to prevent stagnation. Recommended minimum circulation rates within the coolant lines are as follows:

- 2 m/s during normal operation
- 30 cm/s during standby mode

It is recommended that a circulation rate of 10 m/s be established within the tube itself. When it is necessary to turn the coolant flow completely off, the cooling system should be restarted, and allowed to return to a minimum of 1 MΩ-cm resistivity before energizing the tube.

The regeneration loop is typically capable of maintaining the cooling system such that the following maximum contaminant levels are not exceeded:

- Copper: 0.05 ppm by weight
- Oxygen: 0.5 ppm by weight
- CO_2: 0.5 ppm by weight
- Total solids: 3 ppm by weight

These parameters represent maximum levels; if the precautions outlined in this section are taken, actual levels will be considerably lower.

If the cooling system water temperature is allowed to reach 50°C, it will be necessary to use cartridges in the coolant regeneration loop that are designed to operate at elevated temperatures. Most ordinary cartridges will decompose in high-temperature service.

Condensation

The temperature of the input cooling water is an important consideration for proper operation of the cooling system [1]. If the air is humid and the cooling water is cold, condensation will accumulate on the surfaces of pipes, tube jackets, and other parts carrying water. This condensation may decrease the surface leakage resistance, or drops of water may fall on electric components, causing erratic operation or system failure. Some means is necessary, therefore, to control the temperature of the incoming water to keep it above the dew point. Such control is rather easy in a closed cooling system, but in a system that employs tap water and drains the exhaust water into a sewer, control is difficult.

Preventive Maintenance

Through electrolysis and scale formation, hard water may cause a gradual constriction of some parts of the water system [1]. 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*. The target elements should be checked periodically and replaced when they have disintegrated.

To extend the life of the resin beds in the purification loop, all the coolant lines should be flushed with a nonsudsing detergent and a citric acid solution,[1] then rinsed repeatedly with tap water before initially connecting the resin beds and filling with distilled or filtered deionized water. It is also good practice to sterilize the coolant lines with a chlorine solution[2] before filling to prevent algae and/or bacteria growth.

8.2.3 Vapor-Phase Cooling

Vapor-phase cooling offers several advantages over conventional water cooling systems by exploiting the latent heat of the evaporation of water [1]. Raising the temperature of 1 g of water from 40 to 70°C (as in a water system) requires 30 calories of energy. Transforming 1 g 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 20 times as much energy as in a water cooling system. Power densities as high as 135 W/cm^2 of effective internal-anode surface can be 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 100°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.

To achieve the most efficient heat transfer, the anode must be structured to provide for optimum contact with the water in the boiler. Figure 8.13 shows several examples.

Because the boiler usually is at a high potential relative to ground, it must be insulated from the rest of the system. The boiler typically is mounted on insulators, and the steam and water connections are made through insulated tubing. High-voltage standoff

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1 Cirtic acid solution mixtures vary; consult tube manufacturer.
2 Chlorine solution: sodium hypochlorite bleach added in an amount sufficient to give the odor of chlorine in the circulating water.

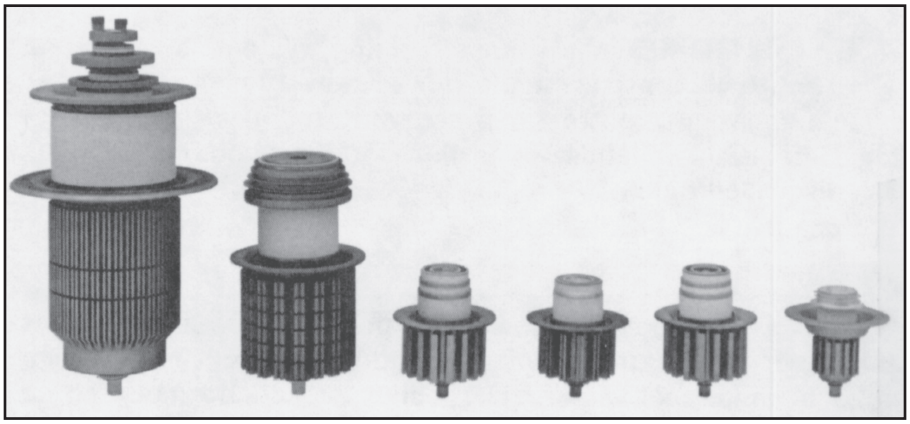

Figure 8.13 Vapor-phase-cooled tubes removed from their companion boilers. (*Courtesy of Varian/Eimac.*)

is more easily accomplished in a vapor-phase system than in a water-cooled system because of the following factors:

- There is a minimum of contamination because the water is constantly being redistilled.
- There is inherently higher resistance in the system because of the lower water-flow rate. The water inlet line is of a smaller diameter, resulting in greater resistance.

In a practical system, a 2-ft section of insulating tubing on the inlet and outlet ports is capable of 20 kV standoff.

Because of the effects of *thermosiphoning*, natural circulation of the water eliminates the need for a pump in most systems.

The dramatic increase in heat absorption that results from converting hot water to steam is repeated in reverse in the condenser. As a result, a condenser of much smaller thermal capacity is required for a vapor-phase system as opposed to a water-cooled system. For example, in a practical water-cooled system, water enters the heat exchanger at 70°C and exits at 40°C; the mean temperature is 55°C. For an ambient external temperature of 25°C, the mean differential between the water and the heat sink (air) is 30°C. The greater the differential, the more heat transferred. In a practical vapor-phase-cooled system, water enters the heat exchanger as steam at 100°C and exits as water at 100°C; the mean temperature is 100°C. For an ambient external temperature of 25°C, the mean differential between the vapor/water and the heat sink is 75°C. In this example, the vapor-phase condenser is nearly three times more efficient than its water-cooled counterpart.

Note that the condenser in a vapor-phase system may use either air or water as a heat sink. The water-cooled condenser provides for isolation of the PA tube cooling system

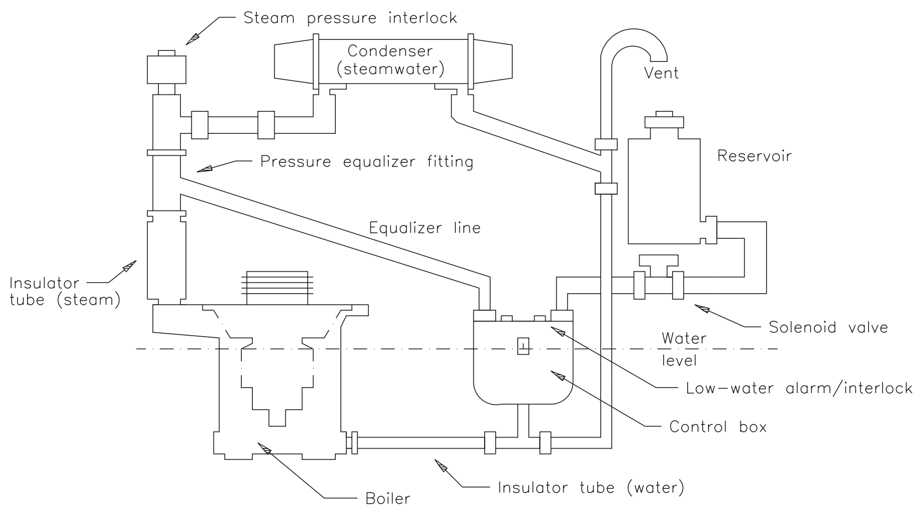

Figure 8.14 Vapor-phase cooling system for a power tube.

from the outside world. This approach may be necessary because of high voltage or safety reasons. In such a system, the water is considered a *secondary coolant*.

Where air-cooled condensers are preferred, the 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.

A typical vapor-phase cooling system is shown in Figure 8.14. It consists of the following elements:

- Power tube
- Boiler
- Condenser
- Insulated tubing
- Control box
- Reservoir
- Associated plumbing

Anode Design

The success of vapor-phase cooling is dependent on anode and boiler designs that allow a tube to operate at a temperature that results in maximum heat dissipation [1].

The most common approach has been to incorporate thick vertical fins on the exterior of the anode to achieve a radial temperature gradient on the surfaces submerged in water. In this way, a hot spot does not cause instantaneous runaway of the tube; only the average fin temperature increases, and this merely shifts the temperature range to a somewhat higher level. The temperatures of the fins typically vary from approximately 110°C at the tip to about 180°C at the root. With an average overall fin temperature of approximately 115°C, for example, the average transferred heat flux is on the order of 60 W/cm^2.

When operating at low dissipation levels, boiling takes place at the root of the fin. Increasing power density causes this boiling area to move out toward the end of the fin until, at rated dissipation levels, boiling takes place on the outer half of the fins. Good design dictates that the anode fin outer edge always remain at less than 125°C.

Anode shape is also important in assuring good cooling by breaking up the sheath of vapor that might tend to form at the surfaces. To a point, the more complicated the shape, the more efficient the anode cooler. Horizontal slots often are milled into the vertical fins to provide more area and to break up bubbles. The more vigorous the boiling action, the lower the possibility that an insulating vapor sheath will form. One design—known as the "pineapple"—carries this idea to the extreme, and incorporates square "knobs" all around the anode to provide dozens of heat-radiating surfaces. The more conventional finned anode, however, is generally adequate and less costly to fabricate.

The *holed anode* is another popular design for lower power densities (up to 100 W/cm^2). In this design, a heavy cylindrical anode is made with vertical holes in the outside wall. Vapor, formed by the boiling of water within the holes, is siphoned upward through the holes to the top of the boiler. This type of cooler always operates below the calefaction point and is used in smaller tube types. The concept is illustrated in Figure 8.15.

Boiler

The boiler supports the power tube and contains the water used for cooling [1]. 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, tilt should be limited to less than 2° to ensure that the anode is covered with water and that the steam outlet is clear. Figure 8.16 shows a 4CV35,000A tetrode mounted in a boiler.

The anode flange of the tube 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-insulated tubing. A *target* to inhibit electrolytic action is provided in the inlet water fitting.

In most cases the boiler is at a high potential relative to ground. Therefore, it must be electrically insulated from the rest of the system. The boiler is mounted on insulators, and the steam and water connections are made through insulating tubing. Boilers can be

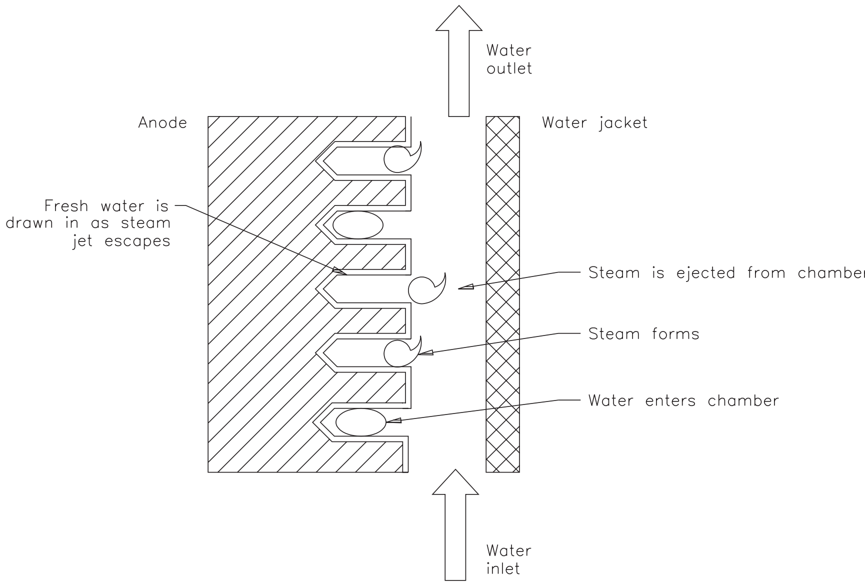

Figure 8.15 Cross section of a *holed anode* design for vapor-phase cooling.

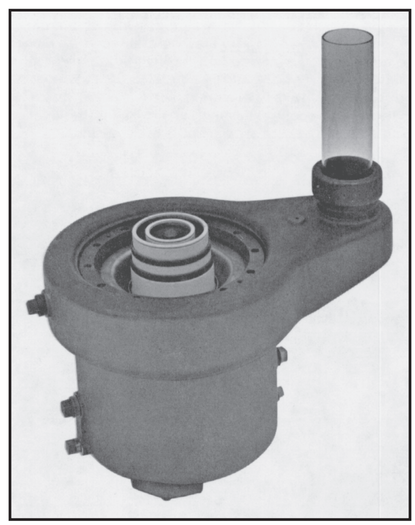

Figure 8.16 A 4CV35,000A tetrode mounted in its boiler assembly. (*Courtesy of Varian*.)

constructed with provisions for mounting multiple tubes in parallel. In such an arrangement, a single water inlet and steam outlet fitting typically would be used.

Common anode/boiler hardware is well suited to RF amplifiers operating up into the HF band, which typically use conventional tuned circuits. Operation in systems at higher frequencies, however, becomes more complicated than water cooling, and cer-

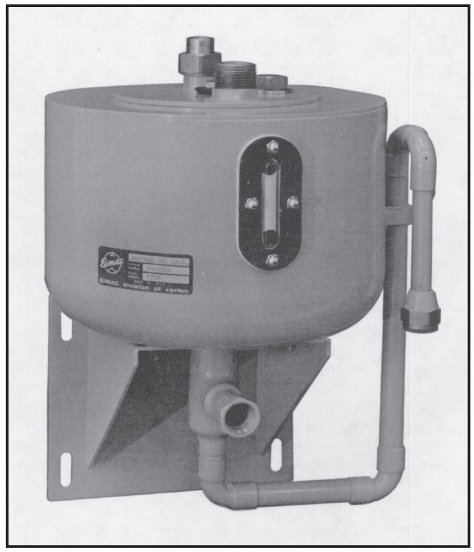

Figure 8.17 Control box for a vapor-phase cooling system. (*Courtesy of Varian.*)

tainly more complicated than air cooling. The cooling system in an air-cooled RF generator does not interfere with the proper operation of the cavity; it is invisible to the cavity. Water cooling introduces some compromises and/or adjustments in the cavity, which can be readily overcome. Vapor-cooled tubes, however, require special design attention for successful use.

Insulating Tubing

The length of the steam and water insulating lines varies with individual installation requirements, but will always be shorter than would be needed in a circulating water system [1]. The length of the insulating tubing is determined by the following considerations:

- The voltage to be applied to the tube anode
- Purity of the water
- Volume of returned cooling water

Control Box

The function of the control box is to monitor and adjust the water level in the boiler [1]. A typical box is shown in Figure 8.17. The control box, an airtight vessel containing an overflow siphon and two float switches, also serves as a partial reservoir. When the water level drops approximately 1/4 in below the recommended level, the first switch is closed. This signal may be used, at the same time, to activate a solenoid-controlled water valve to admit more distilled water from an external reservoir; it also may actuate a warning alarm.

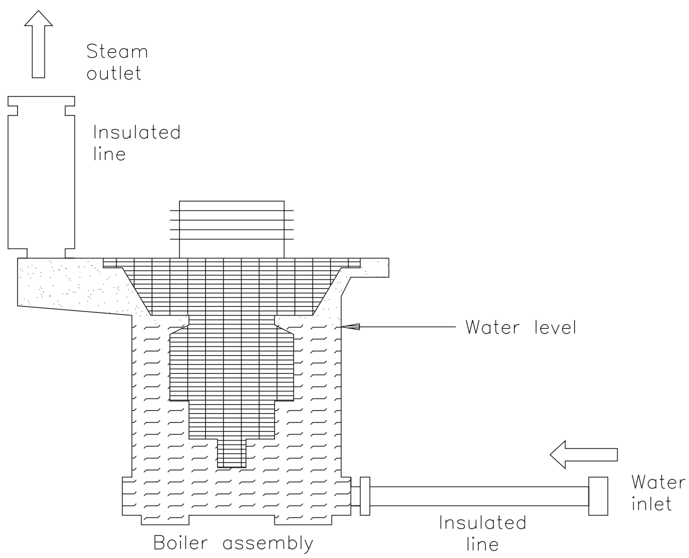

Figure 8.18 Cutaway view of a boiler and tube combination.

The second float switch is operated if the water level drops approximately 1/2 in below the optimum level. This would be tantamount to a water system failure; the switch would be used to open the control circuit interlocks and remove power from the tube.

For the control box to perform its protective function properly, the water-level mark must be precisely in line with the water-level mark on the boiler. For electrical reasons, the control box generally is mounted some distance from the boiler, and therefore leveling of the two components must be carefully checked during installation. Figure 8.18 shows a cutaway drawing of a classic boiler and tube combination. Figure 8.19 is a cutaway drawing of a control box, showing the position of the float switches and the overflow pipe.

During extended operation, some quantity of water and steam being circulated through the condenser will be lost. The amount is dependent on the size of the system. The water level in the boiler, therefore, will gradually drop. The use of the control box as a reservoir minimizes this effect. In large or multiple-tube installations, an auxiliary reservoir is connected to the control box 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 8.20.

Equalizer Line

For the control box to duplicate the same pressure conditions that exist in the boiler, the vapor-phase system must be fitted with an equalizer line [1]. This length of tubing connects the steam side of the system with the top of the control box. As partial steam

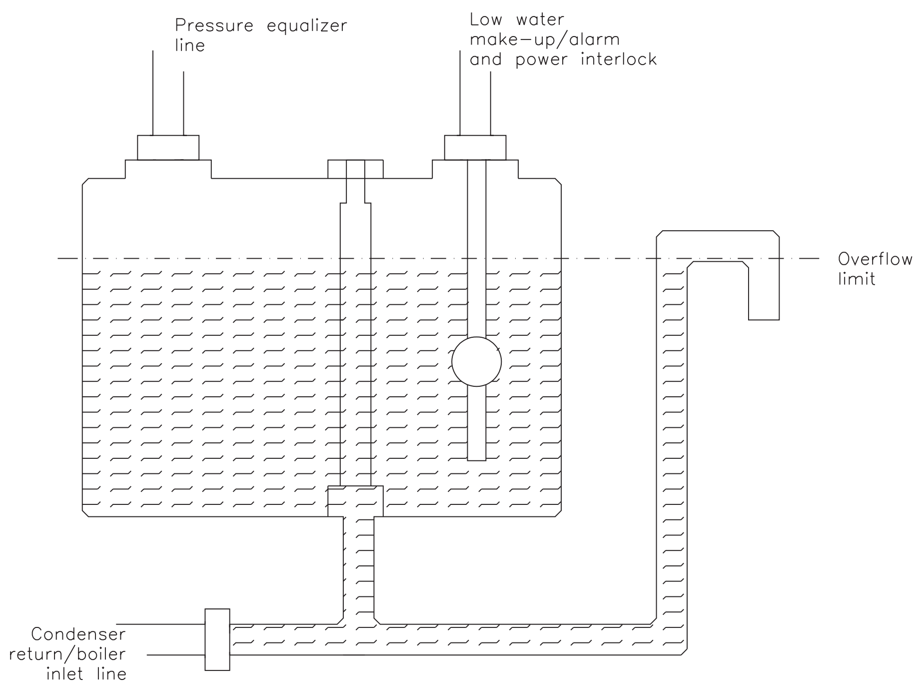

Figure 8.19 Cutaway view of a control box.

pressure begins to build up in the boiler, the equalizer line allows this same pressure to appear in the control box. Although the steam pressure is low, less than 0.5 psi above atmosphere, an error in the operation of the control box would be introduced unless the vessel were equalized.

The fitting used to connect the equalizer line to the steam outlet tube must be constructed to prevent a venturi effect from developing 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 8.21.

Condenser

Both air-cooled and water-cooled condensers are available for vapor cooling systems [1]. Choose condensers with good reserve capabilities and low pressure drop. Air- and water-cooled condensers may be mounted in any position, provided 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 steam.

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 must be used to re-

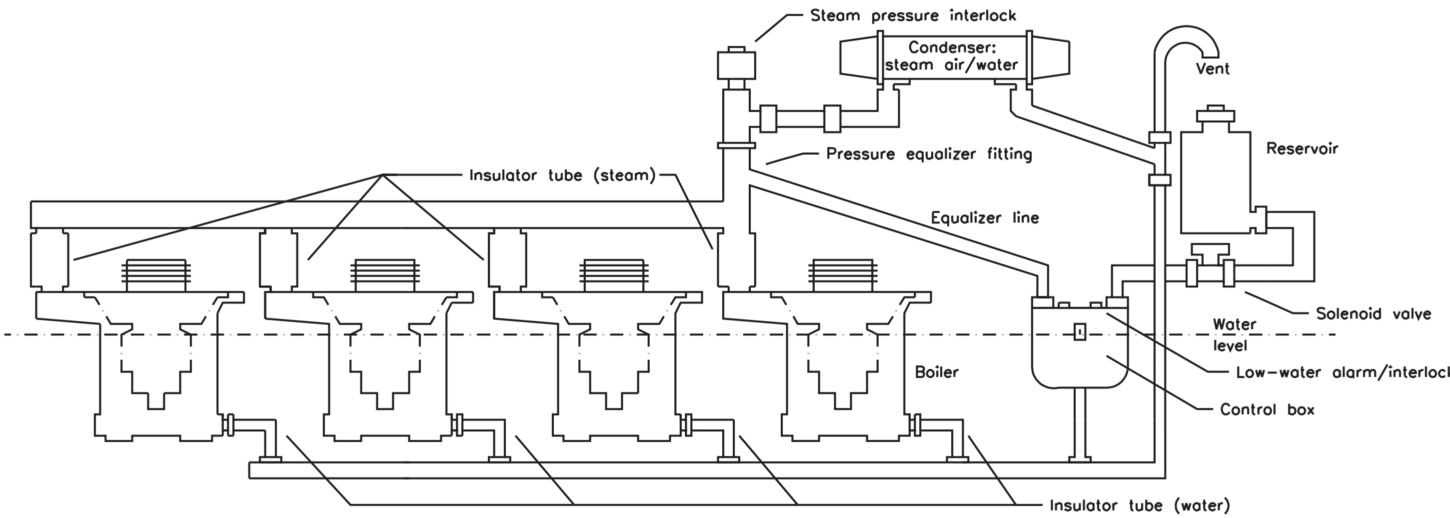

Figure 8.20 Typical four-tube vapor cooling system with a common water supply.

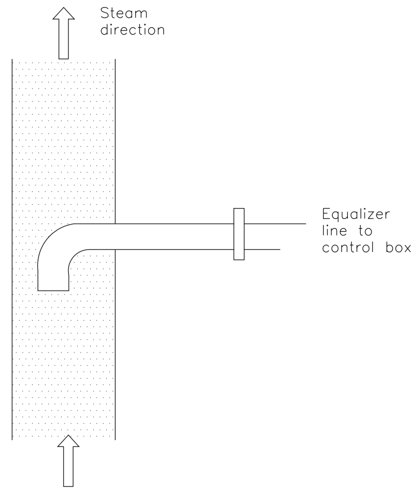

Figure 8.21 Cutaway view of a pressure equalizer fitting.

turn water to the boiler. This arrangement is recommended for the "steam-out-the-bottom" boiler system, as illustrated in Figure 8.22.

Pressure Interlock

Most tube manufacturers recommend the use of a steam pressure interlock switch on the steam or inlet side of the condenser [1]. This switch, set to about 0.5 lbs/in^2, is used as a power interlock that senses abnormal steam pressure resulting from constrictions in the condenser or piping.

Piping

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

The diameter of water return piping from the condenser to the control box will vary from 3/4 to 1-3/4 in, depending again on the power level. This tubing should be the same diameter as the boiler inlet water fitting. It also should be sloped so that water or vapor pockets are not allowed to form, and it 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 made at the lowest physical level of the system.

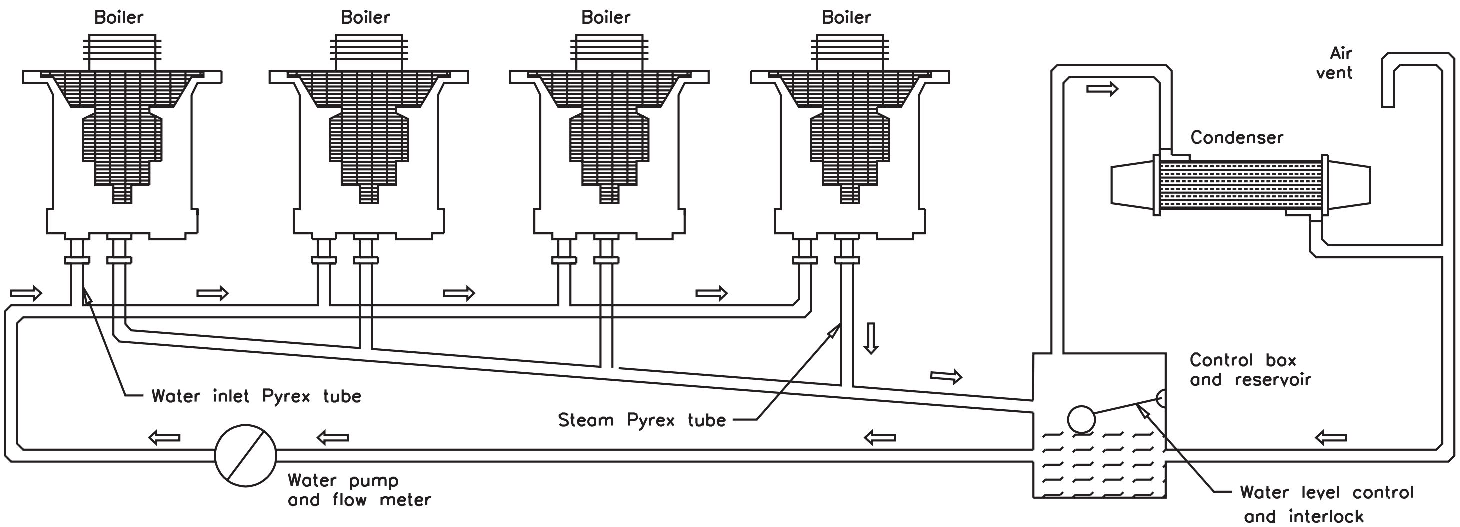

Figure 8.22 Typical four-tube vapor cooling system using "steam-out-the-bottom" boilers.

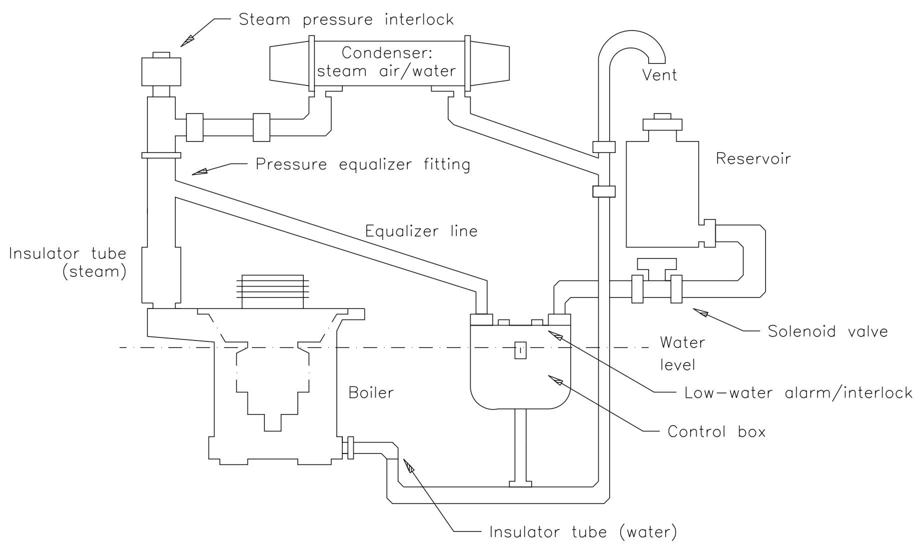

Figure 8.23 Vapor cooling system incorporating a reservoir of distilled water.

The equalizer line also should 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

Figure 8.23 shows a typical vapor cooling system with provisions to allow additional water into the control box [1]. An auxiliary reservoir is connected through a solenoid-operated water valve to the controller. When water loss resulting from evaporation causes the water level in the boiler and the control box to drop about $\frac{1}{4}$ in 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.

Alternative Vapor Cooling Systems

The systems described thus far are "classic" designs in which a separate tube, boiler, condenser, and level control box are used [1]. Variations on this basic scheme are numerous. One such alternative system, offered for use with large power tubes, utilizes a "steam-out-the-bottom" boiler. This configuration makes it possible to keep the steam and water systems, plus the plumbing, below the tubes. This configuration often simplifies the electrical design of the amplifier or oscillator. Figure 8.24 shows a typical boiler used in this cooling technique.

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

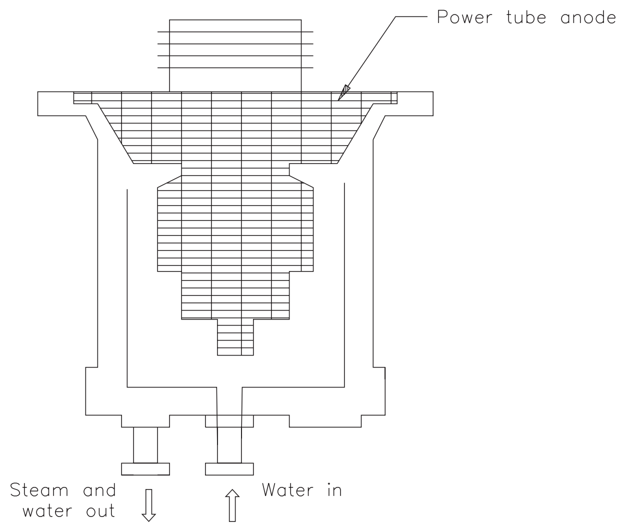

Figure 8.24 Cutaway view of a "steam-out-the-bottom" boiler.

pressure out 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 include a water-flow interlock and water-level switch in the control box to ensure an adequate supply of coolant.

Maintenance

Maintenance problems associated with circulating water systems are practically eliminated in a vapor cooling system [1]. As mentioned previously, systems can be designed to eliminate all rotating machinery or moving parts. Good engineering practice does, however, dictate periodic maintenance. The glass insulator tubes should be inspected occasionally to be sure they contain no deposits that might cause high-voltage flashover. Water conductivity can be checked by measuring the dc resistance, as in a typical circulating water system. The water should be replaced if the dc resistance drops below 1.0 MΩ-cm.

In practice, a vapor-cooled system will remain cleaner longer than a water-cooled system. In the vapor-cooled boiler, the water is continuously 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 removed easily. The periods between equipment shutdown for draining and cleaning will be at least twice as long for a 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, if necessary, replaced. At the same time, the inside of the boiler and the control box can be inspected and cleaned as needed. The electrolytic *target* should be replaced whenever its metallic end is no longer visible in the inlet water line.

8.2.4 Temperature Measurements

Before completing any design employing power tubes, check temperatures in critical areas, such as metal/ceramic seals and (except for water- and vapor-cooled types) the anode just above and below the cooling fins [1]. Another critical area on many medium and large tubes of coaxial design is the central part of the base, which is often recessed and may need special cooling provisions. Electrical contact to the tube terminals is usually by copper-beryllium collets, which should not exceed a temperature of 150°C for any extended period of time. A number of manufacturers make temperature-sensitive paints that are useful for such measurements.[3] "Crayon-type" indicators are also available, in a wide range of temperatures. Conventional temperature measuring-techniques may be affected by the radio frequency energy concentrated at the tube and nearby components. Furthermore, because all power tubes operate at high voltage, there is danger of electric shock with directly connected devices.

When a temperature-sensitive paint or crayon is used for measurement, it must be remembered that many of the areas of concern are vacuum seals involving relatively thin metal. It is important, therefore, that the indicator material be noncorrosive.

Considering the importance of tube element temperatures, every design must be evaluated carefully. All power tubes carry an absolute maximum temperature rating for the seals and envelope, and in the case of an external-anode forced-air-cooled tube, for the anode core itself. Operation above the rated maximum can cause early tube failure. Where long life and consistent performance are important factors, it is normally desirable to maintain tube temperatures comfortably below the rated maximum.

The equipment operator has the ultimate responsibility of making sure that the power tubes used in the system are operating within specified ratings. Most current tube designs use a ceramic envelope and an externally mounted anode or collector. The only visible sign of excessive temperature may be the cosmetic plating beginning to darken or turn black (oxidize). By then, significant damage may have occurred.

"Crayon" Temperature Measurement

When a crystalline solid is heated, a temperature will be reached at which the solid changes sharply to a liquid [1]. This melting point has a definite, reproducible value that is virtually unaffected by ambient conditions that may cause errors in other temperature-sensing methods. For example, fusible temperature indicators are practical in induction heating and in the presence of static electricity or ionized air around electric equipment, where electronic means of measuring temperatures often function erratically.

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3 *Tempilaq* is one such product (Tempil Division, Big Three Industrial Gas and Equipment Co., South Plainfield, NJ).

The most popular type of fusible indicator is a temperature-sensitive stick closely resembling a crayon, with a calibrated melting point. These crayon-type indicators are made in 100 or so different specified temperature ratings in the range of 100 to 2500°F. Typically, each crayon has a temperature-indicating accuracy within 1 percent of its rating. The workpiece to be tested is marked with the crayon. When the workpiece attains the predetermined melting point of the crayon, the mark instantly changes from a solid to a liquid phase (liquefies), indicating that the workpiece has reached that temperature.

Under certain circumstances, premarking with crayon is not practical. This is the case if one or more of the following is true:

- A prolonged heating period is experienced.
- The surface is highly polished and does not readily accept a crayon mark.
- The material being marked is one that gradually absorbs the liquid phase of the crayon.

Note that a melted mark, upon cooling, will not solidify at the exact temperature at which it melted. Solidification of a melted crayon mark, therefore, cannot be relied on for exact temperature indication.

Phase-Change Fluid

A phase-changing fluid, or *fusible temperature-indicating lacquer*, offers the greatest flexibility in temperature measurement of a power tube [1]. The lacquer-type fluid contains a solid material of calibrated melting point suspended in an inert, volatile, nonflammable vehicle. As with crayon-type indicators, there are approximately 100 different temperature ratings, covering a range from 100 to 2500°F. Accuracy is typically within 1 percent of the specified value.

The lacquer is supplied in the proper consistency for brushing. If spraying or dipping is desirable as the mode of application, a thinner is available to alter the viscosity without impairing the temperature-indicating accuracy.

Phase-changing lacquers often are used when a smooth or soft surface must be tested, or in situations where the surface is not readily accessible for application of a crayon mark during the heating process. Within seconds after application, the lacquer dries to a dull matte finish, and it responds rapidly when the temperature to be indicated is reached. The response delay of a lacquer mark is only a fraction of a second. This time can be reduced to milliseconds if a mark of minimal thickness is applied.

Upon reaching its rated temperature, the lacquer mark will liquefy. On subsequent cooling, however, the fluid will not revert to its original unmelted appearance but, rather, to a glossy or crystalline coating, which is evidence of its having reached the required temperature. Temperature-indicating lacquers, upon cooling, will not resolidify at the same temperature at which they melted.

If spraying of the phase-change lacquer is to be the sole means of application, the operator may find it more convenient to use an aerosol-packaged form of this material. An aerosol phase-change temperature indicator is identical to the brush-on material in performance and interpretation.

The first commercial form of the fusible indicator was the *pellet*, which continues to be useful in certain applications. Pellets are most frequently employed when extended heating periods are involved, or where a greater bulk of indicator material is necessary. They are also useful when observations must be made from a distance and when air-space temperatures are to be monitored.

Phase-change temperature-indicator pellets are available in flat, 7/16-in-diameter × 1/8-in-thick tablets. For special applications, miniature pellets, 1/8 in × 1/8 in, are also available. The range of 100 to 2500°F covered by the crayon and lacquer-type is, likewise, covered by the pellets. Pellets with coverage extending to 3200°F also may be obtained.

Another variation of the phase-change indicator is the temperature-sensitive label.[4] These self-adhesive-backed monitors consist of one or more heat-sensitive indicators sealed under transparent heat-resistant windows. The centers of the indicator circles turn from white to black at the temperature ratings shown on the label. The change to black is irreversible, representing an absorption of the temperature-sensitive substance into its backing material. After registering the temperature history of the workpiece, the exposed monitor label can be removed and affixed to a service report to remain part of a permanent record.

Selection Process

Fusible temperature indicators and lacquers have at least three major advantages over other methods of determining surface temperature [1]:

- The temperature indications obtained are unquestionably those of the surface being tested. It is not necessary to equilibrate a relatively massive probe with the surface (a probe may conduct heat away from the region being tested), which requires the use of a correction factor to obtain the actual surface temperature.
- There is no delay in obtaining an indication. Because a mark left by a crayon or a lacquer is of extremely small mass, it attains rapid equilibrium with the surface. There is no conduction of heat away from the surface, which would prolong response time and result in erroneously low temperature readings.
- The technique is simple and economical. Determination of surface temperature by most other means requires technical competence and skill and, in some cases, sophisticated instrumentation. Accurate surface temperature readings can be obtained with fusible indicators and lacquers with little effort, training, and expense.

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4 *Temp-Plate* is one such product (Williams-Wahl Corp., Santa Monica, CA).

There are numerous instances, particularly in determining heat distribution in complex systems, in which the relative simplicity of fusible indicators and lacquers makes surface temperature investigations feasible.

8.2.5 Air-Handling System

All modern air-cooled PA tubes use an air-system socket and matching chimney for cooling [1]. The chimney is designed to be an integral part of the tube cooling system. Operation without the chimney may significantly reduce airflow through the tube and result in overdissipation of the device. It also is possible that operation without the proper chimney could damage other components in the circuit because of excessive radiated heat. Normally, the tube socket is mounted in a pressurized compartment so that cooling air passes through the socket and is guided to the anode cooling fins, as illustrated in Figure 8.25.

Cooling of the socket assembly is important for proper cooling of the tube base and for cooling the contact rings of the tube itself. The contact fingers used in the collet assembly of a socket typically are made of beryllium copper. If subjected to temperatures above 150°C for an extended period of time, the beryllium copper will lose its temper (springy characteristic) and will no longer make good contact with the base rings of the device. In extreme cases, this type of socket problem may lead to arcing, which can burn through the metal portion of the tube base ring. Such an occurrence ultimately may lead to catastrophic failure of the device because of a loss of the vacuum envelope. Other failure modes for a tube socket include arcing between the collet and tube ring, which can weld a part of the socket and tube together. The result is failure of both the tube and the socket.

8.3 Operating Environment

Long-term reliability of a power vacuum tube requires regular attention to the operating environment. Periodic tests and preventive maintenance are important components of this effort. Optimum performance of the cooling system can be achieved only when all elements of the system are functioning properly.

8.3.1 Air-Handling System

The temperature of the intake air supply is a parameter that is usually under the control of the end user. The preferred cooling air temperature is typically no higher than 75°F, and no lower than the room dew point. The air temperature should not vary because of an oversized air-conditioning system or because of the operation of other pieces of equipment at the facility. Monitoring the PA tube exhaust stack temperature is an effective method of evaluating overall RF system performance. This can be easily accomplished. It also provides valuable data on the cooling system and final stage tuning.

Another convenient method for checking the efficiency of the transmitter cooling system over a period of time involves documenting the back pressure that exists within

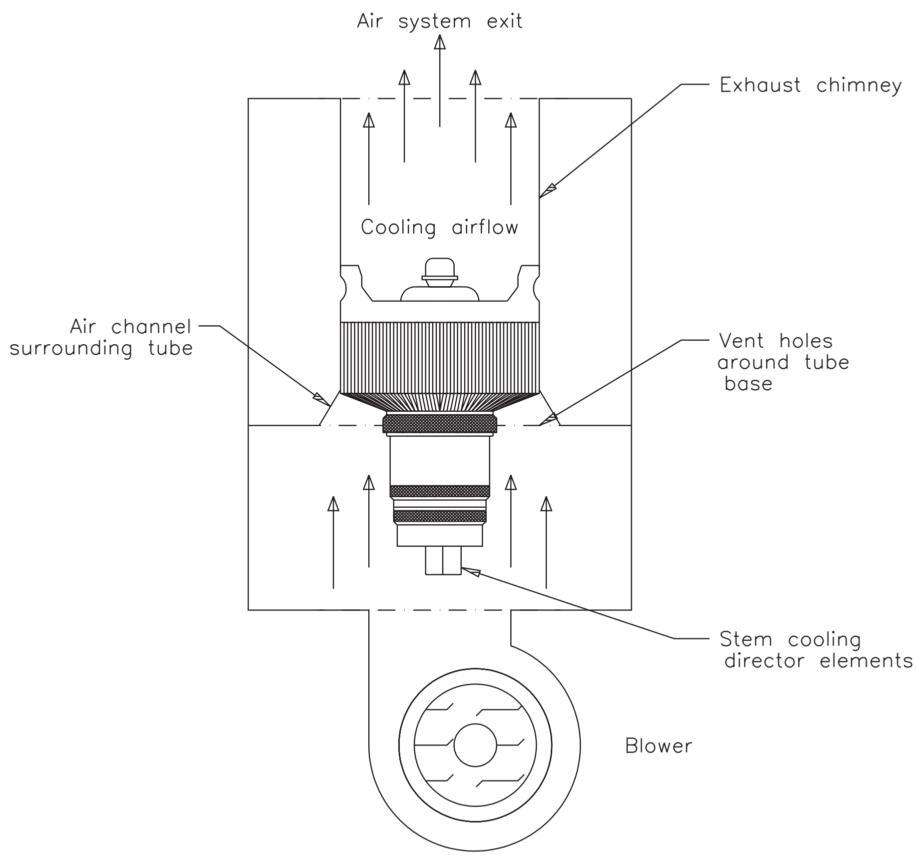

Figure 8.25 Airflow system for an air-cooled power tube.

the PA cavity. This measurement is made with a *manometer*, a simple device that is available from most heating, ventilation, and air-conditioning (HVAC) suppliers. The connection of a simplified manometer to a transmitter PA output compartment is illustrated in Figure 8.26.

By charting the manometer readings, it is possible to accurately measure the performance of the transmitter cooling system over time. Changes resulting from the buildup of small dust particles (*microdust*) may be too gradual to be detected except through back-pressure charting. Deviations from the typical back-pressure value, either higher or lower, could signal a problem with the air-handling system. Decreased PA input or output compartment back pressure could indicate a problem with the blower motor or an accumulation of dust and dirt on the blades of the blower assembly. Increased back pressure, on the other hand, could indicate dirty PA tube anode cooling fins (for the input compartment case) or a buildup of dirt on the PA exhaust ducting (for the output compartment case). Either condition is cause for concern. A system suffering from re-

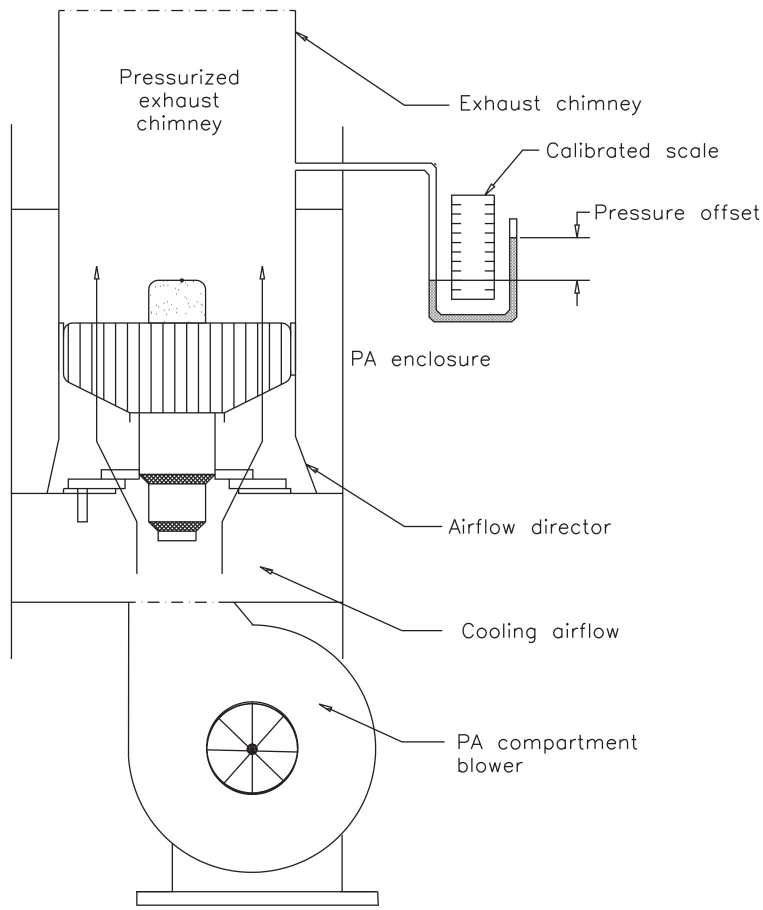

Figure 8.26 A manometer device used for measuring back pressure in the PA compartment of an RF generator.

duced air pressure into the PA compartment must be serviced as soon as possible. Failure to restore the cooling system to proper operation may lead to premature failure of the PA tube or other components in the input or output compartments. Cooling problems do not improve with time; they always get worse.

Failure of the PA compartment air-interlock switch to close reliably may be an early indication of impending trouble in the cooling system. This situation could be caused by normal mechanical wear or vibration of the switch assembly, or it may signal that the PA compartment air pressure has dropped. In such a case, documentation of manometer readings will show whether the trouble is caused by a failure of the air pressure switch or a decrease in the output of the air-handling system.

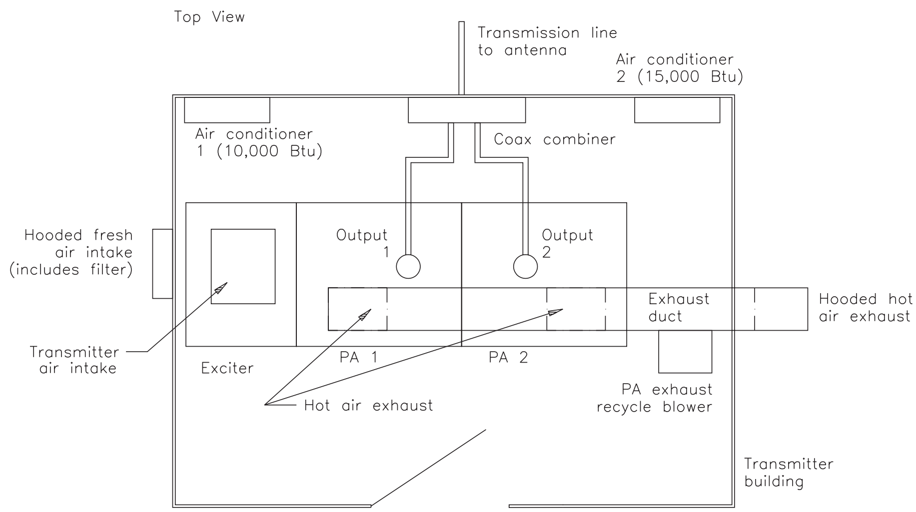

Figure 8.27 A typical heating and cooling arrangement for a high-power transmitter installation. Ducting of PA exhaust air should be arranged so that it offers minimum resistance to airflow.

8.3.2 Air Cooling System Design

Cooling system performance in an RF generator is not necessarily related to airflow volume. The cooling capability of air is a function of its mass, not its volume. The designer must determine an appropriate airflow rate within the equipment and establish the resulting resistance to air movement. A specified static pressure that should be present within the ducting of the transmitter can be a measure of airflow. For any given combination of ducting, filters, heat sinks, RFI honeycomb shielding, tubes, tube sockets, and other elements in the transmitter, a specified system resistance to airflow can be determined. It is important to realize that any changes in the position or number of restricting elements within the system will change the system resistance and, therefore, the effectiveness of the cooling. The altitude of operation is also a consideration in cooling system design. As altitude increases, the density (and cooling capability) of air decreases. A calculated increase in airflow is required to maintain the cooling effectiveness that the system was designed to achieve.

Figure 8.27 shows a typical high-power transmitter plant. The building is oriented so that the cooling activity of the blowers is aided by normal wind currents during the summer months. Air brought in from the outside for cooling is filtered in a hooded air-intake assembly. The building includes a heater and air conditioner.

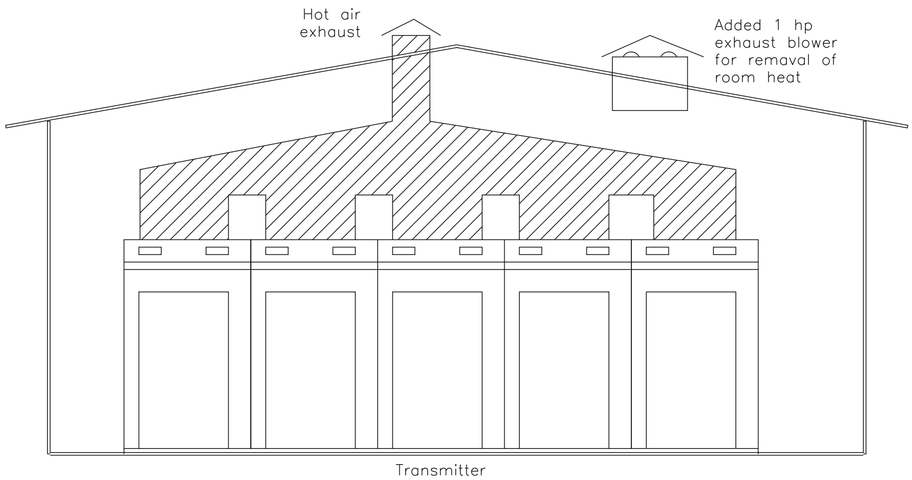

Figure 8.28 Case study in which excessive summertime heating was eliminated through the addition of a 1 hp exhaust blower to the building.

The layout of a transmitter room HVAC system can have a significant impact on the life of the PA tube(s) and the ultimate reliability of the RF generator. Air intake and output ports must be designed with care to avoid airflow restrictions and back-pressure problems. This process, however, is not as easy as it may seem. The science of airflow is complex and generally requires the advice of a qualified HVAC consultant.

To help illustrate the importance of proper cooling system design and the real-world problems that some facilities have experienced, consider the following examples taken from actual case histories:

Case 1

A fully automatic building ventilation system (Figure 8.28) was installed to maintain room temperature at 20°C during the fall, winter, and spring. During the summer, however, ambient room temperature would increase to as much as 60°C. A field survey showed that the only building exhaust route was through the transmitter. Therefore, air entering the room was heated by test equipment, people, solar radiation on the building, and radiation from the transmitter itself before entering the transmitter. The problem was solved through the addition of an exhaust fan (3000 cfm). The 1 hp fan lowered room temperature by 20°C.

Case 2

A simple remote installation was constructed with a heat-recirculating feature for the winter (Figure 8.29). Outside supply air was drawn by the transmitter cooling system blowers through a bank of air filters, and hot air was exhausted through the roof. A

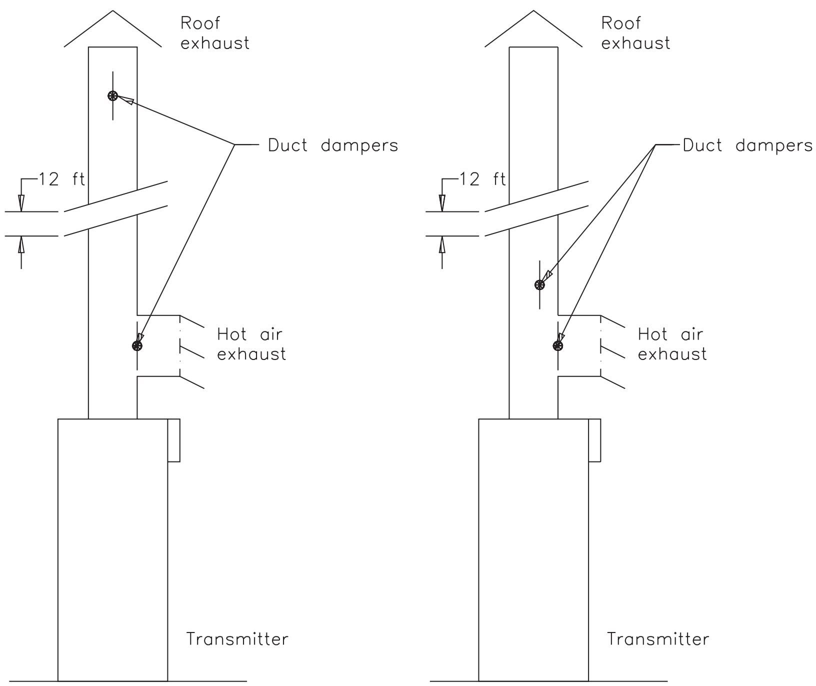

Figure 8.29 Case study in which excessive back pressure to the PA cavity was experienced during winter periods, when the rooftop damper was closed. The problem was eliminated by repositioning the damper as shown.

small blower and damper were installed near the roof exit point. The damper allowed hot exhaust air to blow back into the room through a tee duct during the winter months. For summer operation, the roof damper was switched open and the room damper closed. For winter operation, the arrangement was reversed. The facility, however, experienced short tube life during winter operation, even though the ambient room temperature during winter was not excessive.

The solution involved moving the roof damper 12 ft down to just above the tee. This eliminated the stagnant "air cushion" above the bottom heating duct damper and significantly improved airflow in the region. Cavity back pressure was, therefore, reduced. With this relatively simple modification, the problem of short tube life disappeared.

Case 3

An inconsistency regarding test data was discovered within a transmitter manufacturer's plant. Units tested in the engineering lab typically ran cooler than those at the manufacturing test facility. Figure 8.30 shows the test station difference, a 4-ft exhaust stack that was used in the engineering lab. The addition of the stack increased

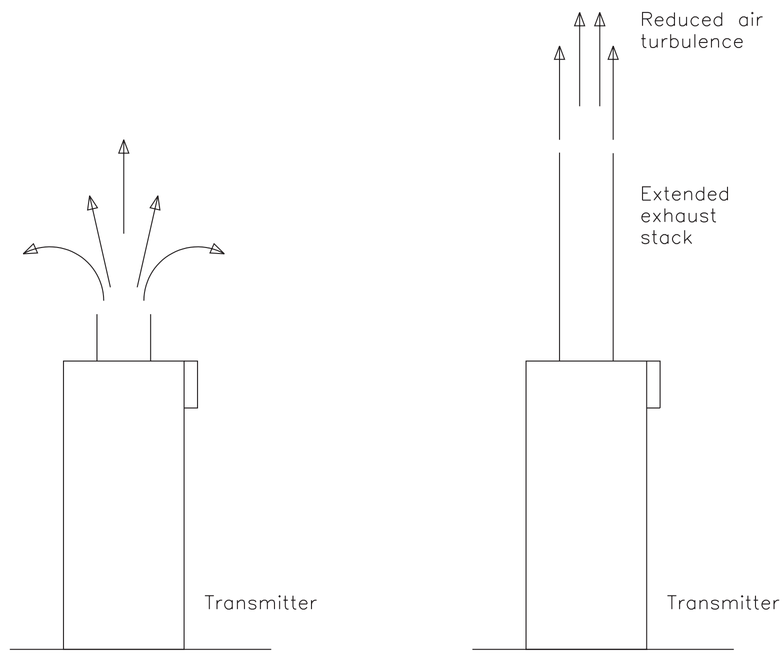

Figure 8.30 Case study in which air turbulence at the exhaust duct resulted in reduced airflow through the PA compartment. The problem was eliminated by adding a 4-ft extension to the output duct.

airflow by up to 20 percent because of reduced air turbulence at the output port, resulting in a 20°C decrease in tube temperature.

These examples point out how easily a cooling problem can be caused during HVAC system design. All power delivered to the transmitter either is converted to RF energy and sent to the antenna or becomes heated air (or water). Proper design of a cooling system, therefore, is a part of transmitter installation that should not be taken lightly.

8.3.3 Site Design Guidelines

There are any number of physical plant designs that will provide for reliable operation of high-power RF systems [3]. One constant, however, is the requirement for tight temperature control. Cooling designs can be divided into three broad classifications:

- Closed site design
- Open site design
- Hybrid design

If the equipment user is to provide adequately for hot air exhaust and fresh air intake, the maximum and minimum environmental conditions in which the equipment will operate must be known. In addition, the minimum cooling requirements of the equipment must be provided by the manufacturer. The following parameters should be considered:

- Site altitude
- Maximum expected outside air temperature
- Minimum expected outside air temperature
- Total airflow through the transmitter
- Air temperature rise through the transmitter
- Air exhaust area

Keep in mind that the recommended cooling capacity for a given RF system applies only to cooling the transmitter; any additional cooling load in the building must be considered separately when selecting the air system components. The transmitter exhaust should not be the only exhaust port in the room because heat from the peripheral equipment would then be forced to go out through the transmitter.

The *sensible-heat load*, then, is the sum of all additional heat loads, including:

- Solar radiation
- Heat gains from equipment and lights
- Heat gains from personnel in the area that is to be cooled

Closed Site Design

Figure 8.31 illustrates a site layout that works well in most climates, as long as the transmitter is small and the building is sealed and well insulated [3]. In fact, this closed configuration will ensure the longest possible transmitter life and lowest maintenance cost. No outside air laden with moisture and contaminants circulates through the transmitter.

At sites using this arrangement, it has been observed that periodic transmitter cleaning is seldom required. In a typical closed system, the air conditioner is set to cool when the room temperature reaches 75 to 80°F. The closed system also uses a louvered emergency intake blower, which is set by its own thermostat to pull in outside air if the room temperature reaches excessive levels (above 90°F). This blower is required in a closed configuration to prevent the possibility of thermal runaway if the air conditioner fails. Without such an emergency ventilation system, the transmitter would recirculate its own heated air, further heating the room. System failure probably would result.

During winter months, the closed system is self-heating (unless the climate is harsh, or the transmitter power output is low), because the transmitter exhaust is not ducted outside but simply empties into the room. Also during these months, the emergency intake blower can be used to draw cold outside air into the room instead of using the air conditioner, although this negates some of the cleanliness advantages inherent to the closed system.

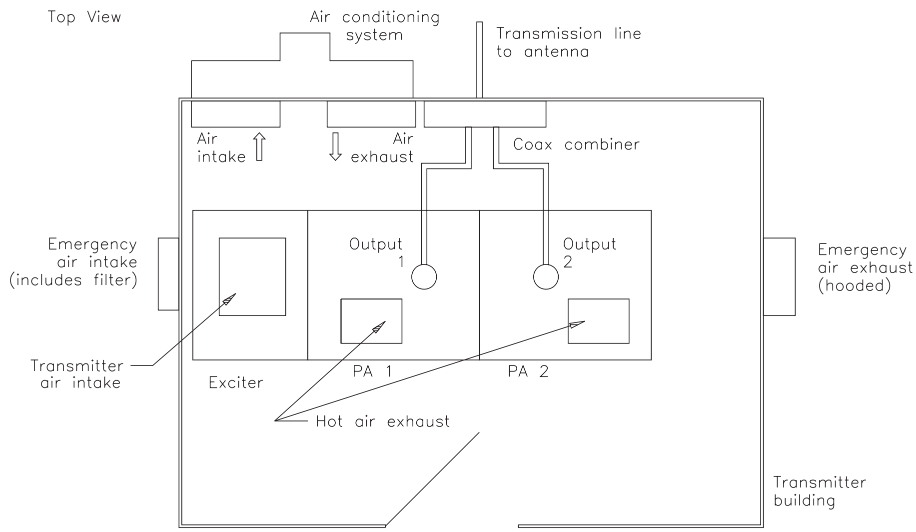

Figure 8.31 Closed site ventilation design, with a backup inlet/outlet system.

An exhaust blower should not be substituted for an intake blower, because positive room pressure is desired for venting the room. This ensures that all air in the building has passed through the intake air filter. Furthermore, the louvered emergency exhaust vent(s) should be mounted high in the room, so that hot air is pushed out of the building first.

The closed system usually makes economic sense only if the transmitter exhaust heat load is relatively small.

Periodic maintenance of a closed system involves the following activities:

- Checking and changing the air conditioner filter periodically
- Cleaning the transmitter air filter as needed
- Checking that the emergency vent system works properly
- Keeping the building sealed from insects and rodents

Open Site Design

Figure 8.32 depicts a site layout that is the most economical to construct and operate [3]. The main attribute of this approach is that the transmitter air supply is not heated or cooled, resulting in cost savings. This is not a closed system; outdoor air is pumped into the transmitter room through air filters. The transmitter then exhausts the hot air. If the duct work is kept simple and the transmitter has a dedicated exhaust port, such a direct exhaust system works adequately. Many transmitters do not lend themselves to

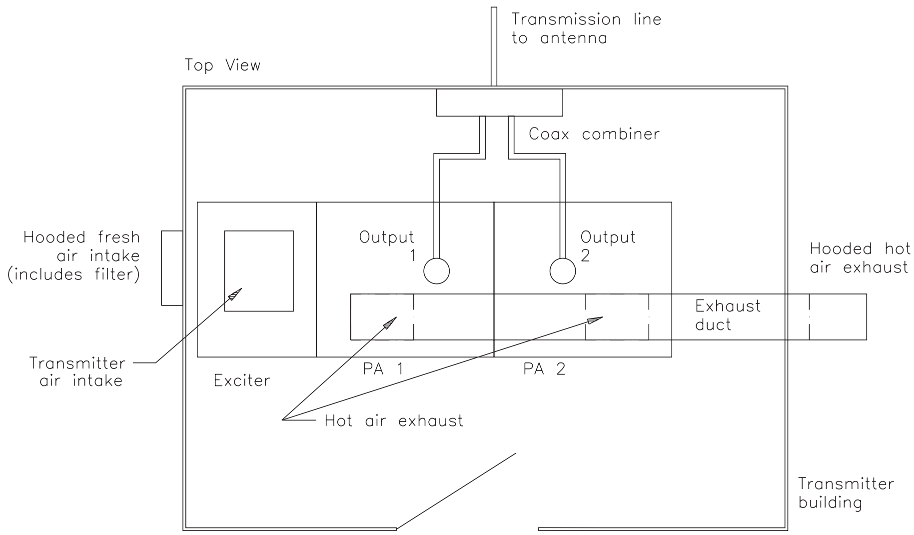

Figure 8.32 Open site ventilation design, using no air conditioner.

a direct exhaust connection, however, and a hood mounted over the transmitter may be required to collect the hot air, as illustrated in Figure 8.33. With a hooded arrangement, it may be necessary to install a booster fan in the system, typically at the wall or roof exit, to avoid excessive back pressure.

When building an open air-circulation system, there are some important additional considerations. The room must be positively pressurized so that only filtered air, which has come through the intake blower and filter, is available to the transmitter. With a negatively pressurized room, air will enter through every hole and crack in the building, and will not necessarily be filtered. Under negative pressure, the transmitter blower also will have to work harder to exhaust air.

The intake blower should be a “squirrel-cage” type rather than a fan type. A fan is meant to move air within a pressurized environment; it cannot compress the air. A squirrel-cage blower will not only move air, but also will pressurize the area into which the air is directed. Furthermore, the intake air blower must be rated for more cubic feet per minute (cfm) airflow than the transmitter will exhaust outside. A typical 20 kW FM broadcast transmitter, for example, will exhaust 500 cfm to 1000 cfm. A blower of 1200 cfm, therefore, would be an appropriate size to replenish the transmitter exhaust and positively pressurize the room.

In moderate and warm climates, the intake blower should be located on a north-facing outside wall. If the air intake is on the roof, it should be elevated so that it does not pick up air heated by the roof surface.

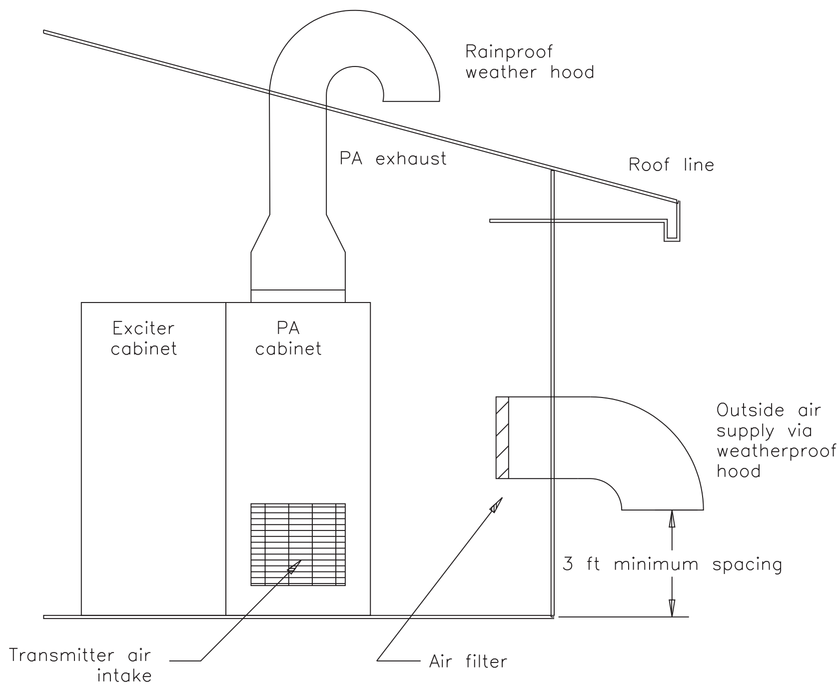

Figure 8.33 Transmitter exhaust-collection hood.

High-quality pleated air filters are recommended. Home-style fiberglass filters are not sufficient. Local conditions may warrant using a double filtration system, with coarse and fine filters in series.

Secure the advice of a knowledgeable HVAC shop when designing filter boxes. For a given cfm requirement, the larger the filtration area, the lower the required air velocity through the filters. This lower velocity results in better filtration than forcing more air through a small filter. In addition, the filters will last longer. Good commercial filtration blowers designed for outdoor installation are available from industrial supply houses and are readily adapted to RF facility use.

The transmitter exhaust may be ducted through a nearby wall or through the roof. Avoid ducting straight up, however. Many facilities have suffered water damage to transmitters in such cases because of the inevitable deterioration of roofing materials. Normally, ducting the exhaust through an outside wall is acceptable. The duct work typically is bent downward a foot or two outside the building to keep direct wind from creating back pressure in the exhaust duct. Minimize all bends in the duct work. If a 90° bend must be made, it should be a large-radius bend with curved *helper* vanes inside the duct to minimize turbulence and back pressure. A 90° L- or T-bend is not recommended, unless oversized and equipped with internal vanes to assist the turning airflow.

For moderate and cool climates, an automatic damper can be employed in the exhaust duct to direct a certain amount of hot exhaust air back into the transmitter build-

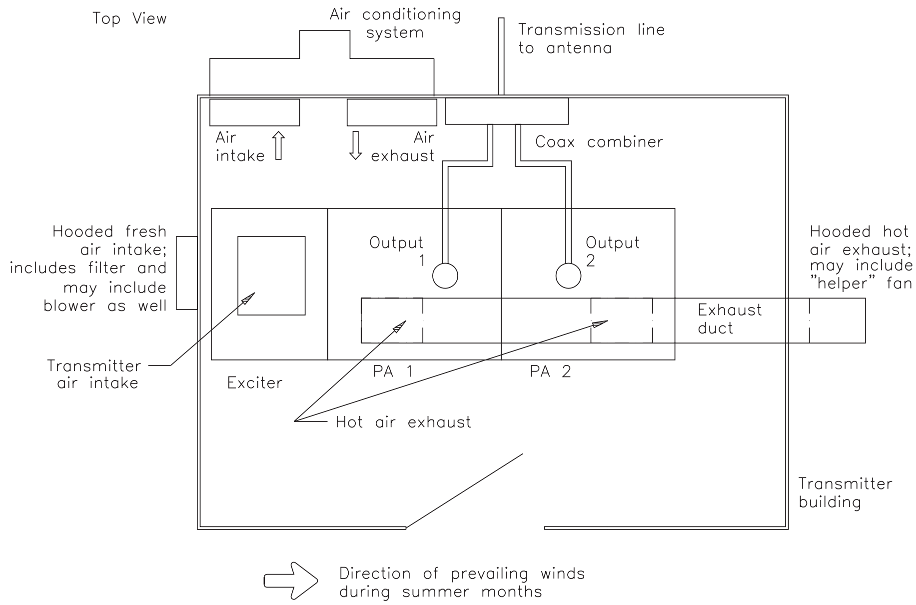

Figure 8.34 Hybrid site ventilation design, using an air conditioner in addition to filtered outside air.

ing as needed for heating. This will reduce outside air requirements, providing clean, dry, heated air to the transmitter during cold weather.

Hybrid Design

Figure 8.34 depicts a hybrid site layout that is often used for high-power transmitters or sites supporting multiple transmitters [3]. As with the layout in Figure 8.32, the room is positively pressurized with clean, filtered air from the outside. A portion of this outside air is then drawn through the air conditioner for cooling before delivery to the transmitter area. Although not all of the air in the room goes through the air conditioner, enough does to make a difference in the room temperature. In humid areas, much of the moisture is removed by the air conditioner. The transmitter exhaust is directed outside.

Such a hybrid system is often the choice for larger transmitter sites where a closed system would prove too costly, but an unconditioned system would run excessively hot during the summer months.

Some closed or hybrid systems use two parallel air conditioners. Most of the time, only one is in use. The thermostats of the units are staggered so that if one cannot keep the air below the ideal operating point, the other will turn on to assist.

8.3.4 Water/Vapor Cooling System Maintenance

The cooling system is vital to any RF generator. In a klystron-based unit, for example, the cooling system may dissipate a large percentage of the input ac power in the form of waste heat in the collector. Pure, distilled water should be used. Deionized water is required unless the isolation of high voltages is unnecessary, as in the case of the collector of a klystron (the collector typically operates at or near ground potential).

Any impurities in the cooling system water eventually will find their way into the water jacket and cause corrosion of the plate or collector. It is essential to use high-purity water with low conductivity, and to replace the water in the cooling system as needed. Efficient energy transfer from the heated surface into the water is necessary for long vacuum tube life. Oil, grease, soldering flux residue, and pipe sealant containing silicone compounds must be excluded from the cooling system. This applies to both vapor- and liquid-conduction cooling systems, although it is usually more critical in the vapor-phase type. The sight glass in a vapor-phase water jacket provides a convenient checkpoint for coolant condition.

In general, greater flows and greater pressures are inherent in liquid-cooled vs. vapor-phase systems, and, when a leak occurs, large quantities of coolant can be lost before the problem is discovered. The condition of gaskets, seals, and fittings, therefore, should be checked regularly. Many liquid-cooled tubes use a distilled water and ethylene glycol mixture. (Do not exceed a 50:50 mix by volume.) The heat transfer of the mixture is lower than that of pure water, requiring the flow to be increased, typically by 25 percent. Greater coolant flow suggests closer inspection of the cooling system after adding the glycol.

The action of heat and air on ethylene glycol causes the formation of acidic products. The acidity of the coolant can be checked with litmus paper. Buffers can be added to the glycol mixture. Buffers are alkaline salts that neutralize acid forms and prevent corrosion. Because they are ionizable chemical salts, the buffers cause the conductivity of the coolant to increase. Consult the power tube manufacturer before adding buffers.

The following general guidelines are recommended for power tube cooling systems:

- The resistivity of the water must be maintained above the minimum level established by the power tube manufacturer. Although recommended values vary, generally speaking, resistivity should be maintained at or above 1 MΩ-cm (at 30ºC) for power tubes operating at a high-voltage, referenced to ground. A resistivity value of 30 kΩ-cm or greater (at 30ºC) is usually sufficient for tubes whose collector operates at or near ground potential (such as a klystron).
- The pH factor must be within the range of 6.0 to 8.0.
- The particulate matter size must not be greater than 50 microns (325 mesh).
- The inlet water temperature must not exceed 70°C, and this temperature should be regulated to ±5ºC.

When the water in the cooling system fails to satisfy any one of these requirements, prompt action is necessary to correct the deficiency. If the water is contaminated, the system must be flushed and replaced with clean water.

Tests for Purity

The recommended method for measuring resistivity, pH, and particulate matter is by use of laboratory instruments. However, the following simple tests should provide sufficient information to determine the general condition of the coolant.

- The appearance of the water is a good general indicator of coolant condition. If the water looks turbid or tastes or smells brackish, it is good practice to change the water and flush the system.
- The pH factor is easily checked by using pH paper or litmus paper. Sold under a variety of trade names, pH paper is available at laboratory supply stores. Directions for use usually are printed on the package.
- Particulate matter and impurities can be checked by using the "foaming test" (described in the next section).
- Resistivity can be measured accurately with a resistance bridge. Generally speaking, if the water does not pass the foaming test, the resistivity will be low as well.

Foaming Test for Water Purity

One of the many factors affecting the life and operating efficiency of vapor-cooled tubes is the purity of the water in the cooling system. If impurities are present, foaming may occur that will inhibit heat transfer, thereby lowering the cooling efficiency of the system. The impurities that most frequently produce foaming are:

- Cleaning-compound residue
- Detergents
- Joint-sealing compounds
- Oily rust preventives in pumps and other components
- Valve-stem packing
- Impurities in tap water

Tests should be conducted periodically to confirm the quality of the coolant in a vapor-phase system. Conduct such tests after each water change, system cleaning, or modification. The following items are required:

- A 1/2-in × 4-in glass test tube with rubber stopper
- A 1-pint glass or polypropylene bottle with cap

The procedure is as follows:

- Fill the cooling system with water, and circulate it until thoroughly mixed (about 30 minutes).
- Drain a sample of water into the bottle, and cool to room temperature.

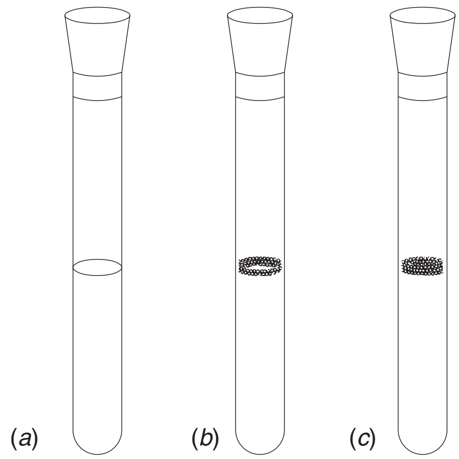

Figure 8.35 Results of the "foaming test" for water purity: (*a*) pure sample, (*b*) sample that is acceptable on a short-term basis, (*c*) unacceptable sample.

- If the water sample stands for more than 1 hour, slowly invert the capped bottle about 10 times. Avoid shaking the bottle because this will create air bubbles in the water. (When the water is static, foaming impurities tend to collect at the surface. This step mixes the sample without generating foam.)
- Using the sample water, rinse the test tube and stopper three times.
- Fill the test tube to the halfway mark with the sample water.
- Shake the test tube vigorously for 15 s.
- Let the sample stand for 15 s.
- Observe the amount of foam remaining on top of the water and compare it with the drawings shown in Figure 8.35.

A completely foam-free water surface and test tube, as illustrated in (*a*), indicates no foam-producing impurities. If the water surface and test tube wall are partially covered with foam, but a circle of clear water appears in the center, the impurity level is temporarily acceptable (*b*). A second test should be made in about one week. If the foam layer completely bridges the inside of the test tube (*c*), the system should be flushed and cleaned.

8.4 References

1. Laboratory Staff, *The Care and Feeding of Power Grid Tubes*, Varian Associates, San Carlos, CA, 1984.
2. Besch, David F., "Thermal Properties," in The Electronics Handbook, Jerry C. Whitaker (ed.), CRC Press, Boca Raton, FL, pp. 127–134, 1996.

3. Harnack, Kirk, "Airflow and Cooling in RF Facilities," *Broadcast Engineering*, Intertec Publishing, Overland Park, KS, pp. 33–38, November 1992.

8.5 Bibliography

"Cleaning and Flushing Klystron Water and Vapor Cooling Systems," Application Engineering Bulletin no. AEB-32, Varian Associates, Palo Alto, CA, February 1982.

Crutchfield, E. B. (ed.), *NAB Engineering Handbook*, 8th Ed., National Association of Broadcasters, Washington, DC, pp. 547–550, 1992.

"Foaming Test for Water Purity," Application Engineering Bulletin no. AEB-26, Varian Associates, Palo Alto, CA, September 1971.

Harnack, Kirk, "Airflow and Cooling in RF Facilities," *Broadcast Engineering*, Intertec Publishing, Overland Park, KS, pp. 33–38, November 1992.

Harper, Charles A., *Electronic Packaging and Interconnection Handbook*, McGraw-Hill, New York, NY, 1991.

"High Power Transmitting Tubes for Broadcasting and Research," Philips Technical Publication, Eindhoven, the Netherlands, 1988.

Integral Cavity Klystrons for UHF-TV Transmitters, Varian Associates, Palo Alto, CA.

Kimmel, E., "Temperature Sensitive Indicators: How They Work, When to Use Them," *Heat Treating*, March 1983.

"Power Grid Tubes for Radio Broadcasting," Thomson-CSF Publication #DTE-115, Thomson-CSF, Dover, NJ, 1986.

"Protecting Integral-Cavity Klystrons Against Water Leakage," Technical Bulletin no. 3834, Varian Associates, Palo Alto, CA, July 1978.

"Temperature Measurements with Eimac Power Tubes," Application Bulletin no. 20, Varian Associates, San Carlos, CA, January 1984.

"Water Purity Requirements in Liquid Cooling Systems," Application Bulletin no. 16, Varian Associates, San Carlos, CA, July 1977.

"Water Purity Requirements in Water and Vapor Cooling Systems," Application Engineering Bulletin no. AEB-31, Varian Associates, Palo Alto, CA, September 1991.

Whitaker, Jerry C., *Maintaining Electronic Systems*, CRC Press, Boca Raton, FL, 1992.

Whitaker, Jerry C., *Radio Frequency Transmission Systems: Design and Operation*, McGraw-Hill, New York, NY, 1990.

Wozniak, Joe, "Using Tetrode Power Amplifiers in High Power UHF-TV Transmitters," *NAB 1992 Broadcast Engineering Conference Proceedings*, National Association of Broadcasters, Washington, DC, pp. 209–211, 1992.