19. Thermal Management

Thermal management of a transmitter means controlling its operating temperatures. It also means heat transfer, but this will happen whether there has been proper thermal management or not.

Power will be dissipated throughout the components of a transmitter, but the dissipation will be most significant where energetic electrons strike the inside surfaces of microwave-tube beam collectors or the surfaces of cathode-facing anodes in triodes and tetrodes. Charge carriers impinging on the collectors and drains of transistors are also responsible for their internal power dissipation. The rate-of-arrival of these charge carriers determines current flow, and their kinetic energy, which is proportional to voltage, determines the energy-deposition rate, or power dissipation.

Few electrical, or even mechanical, transmitter designers are completely comfortable with thermal design. Most know only enough "to get burned," so to speak. However, our knowing that literally "getting burned" is a real possibility should heighten our awareness of, if not our ability to solve, all of the thermally related problems.

To begin with, there are only two basic physical mechanisms for heat transfer: radiation and conduction. Radiation, which has its basis in quantum mechanics, involves emission of electromagnetic waves, or photons, from the surface of the hot body. The rate at which heat will be transferred by radiation from a unit of surface area depends upon the difference between the fourth power of the absolute temperature (in kelvins) of the hot-body surface and the fourth power of the absolute temperature of its surroundings, assuming that the area of the surroundings is much greater than that of the hot body. It is also modified by its emissivity, a coefficient anywhere from zero to one that represents the normalized ability to radiate when compared with a perfect "black-box" radiator.

Unlike radiation, which is most efficient in a vacuum, conduction takes place in solids and fluids (both gaseous and liquid) and is related to molecular motion. Heated molecules are more energetic, and they exchange that energy with neighboring molecules that are cooler or less energetic. Convection is a special case of conduction. It can be either "free," or "natural," or forced. It involves the transfer of heat from a solid to a fluid, or from one fluid to another. Convection is also influenced by the ability of a fluid to move freely and to change its characteristics. For instance, the fluid can become less dense when it is heated, or even freeze, liquefy, or vaporize. Also unlike radiation, conduction has its rate of heat transfer figured differently. The rate of heat transfer by conduction for a given unit of area (normal to the direction of heat flow) is proportional to the difference in temperature, ΔT, between source and sink along the path of heat flow. (Although not directly related to electronics at all, the phenomenon of giant tractor-trailer trucks "losing" their brakes has nothing to do with failure of the air system that actuates them but a failure of brake thermal management. If the truck is heavy enough and going fast enough down a steep-enough grade, the heat generated by the brake friction, which is also transferred primarily by radiation, causes the brake temperature to reach a point where the brake diameter will actually increase due to thermal expansion. When the brakes reach the point where they no longer make contact with the drum, the result is another runaway truck.)

19.1 Heat transfer by radiation

Although the primary means of heat transfer in a transmitter is conduction of one form or another, some heat will be transferred by radiation. A classic example of multi-mode heat transfer is the family of glass-envelope, pulse-rated tetrodes that includes the 4PR250 and the 8960, as well as the 4PR125, 4PR400, and 4PR1000 (see Fig. 11-12). These tubes have anodes made of a special metal called Pyrovac ("pyro" for high-temperature and "vac" for vacuum). If you recall, the anodes are cylindrical and are the outermost electrodes. (The physical format is called radial-beam, external anode.) In these tubes the anode is suspended from the top of the glass envelope, where a glass-metal seal provides a connection to external circuitry. For the seal to be properly cooled, a "heat-radiating connector," which is a short cylindrical piece of aluminum with machined fins, must be attached to the external anode connection. If the current terminating on the anode produces enough power dissipation, the lower end of the anode will glow red. The glow starts at the bottom because the thermal-conduction path to the external anode heat dissipator is the longest from that end. As dissipation increases to its rated maximum, the entire outer surface of the anode will glow red. It will literally be red hot. It will now have reached a temperature within the vacuum of the tube at which it can efficiently transfer heat by radiation. (It has been said that there is—or was—at least one tube engineer who could accurately estimate within a few watts the amount of anode dissipation in such a tube just by observing the hue and extent of the anode glow.)

The problem of heat transfer in outer space is also a formidable one because there is no external molecular medium to receive conducted heat. It is possible to build microwave vacuum tubes using collectors that can operate at temperatures sufficiently high to radiate heat directly into space. Temperatures up to 900°C (1173 K) have been tolerated without serious problems. Solid-state devices, however, must be operated with junction temperatures below about 350°C (623 K), and even then their life expectancies can be seriously shortened. The microwave tube collector enjoys a radiation-cooling effectiveness that is almost 24 (or 16) times that of the solid-state device (and even that assumes that the latter's junction itself can be made to directly radiate into space). In the early days of the Strategic Defense Initiative, it was estimated that the surface area of a radiator required to transfer heat from a solid-state transmitter in a space-based radar, with tolerable surface temperature, would equal that of a football field—including the end zones!

Devices producing RF power that are placed on board rockets using liquefied gas as fuel do have a molecular medium with which to exchange heat (and a cold one at that). Unfortunately, transistors become sluggish and virtually inoperative at cryogenic temperatures, except for a special class called the static-induction transistor. However, recent actual experiments have shown that even conven-

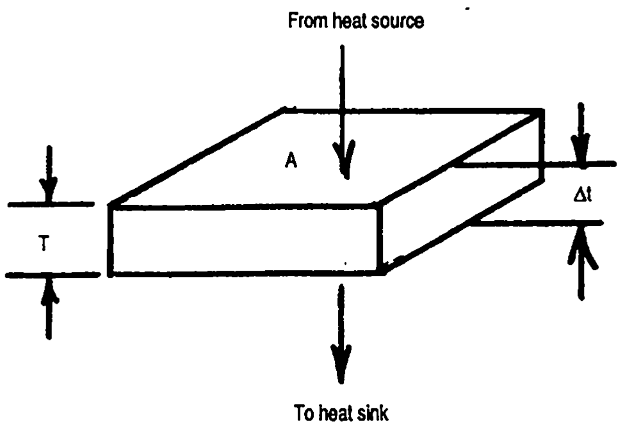


Figure 19-1. The elements of thermal resistance.

tional bipolar transistors can be "insulated" from the cold sink in such a way that they will heat themselves up by their own dissipation to a quasi-functional internal temperature.

19.2 Heat transfer by conduction in solids

No matter what makes up the complete thermal path along which heat is transferred, it invariably begins with conduction in a solid. The anode of a triode

Table 19-1. Thermal resistivity of selected materials.

Material	R (°C-in./W)	Material	R (°C-in./W)
Diamond	0.06	Silicon carbide	2.3
Silver	0.10	Steel (300 series)	2.4
Copper	0.11	Nichrome	3.0
Gold	0.13	Carbon	5.7
Aluminum	0.23	Ferrite	6.3
Beryllia ceramic	0.24	Pyroceram (9606)	11.7
Molybdenum	0.27	Epoxy	24
Brass	0.34	Quartz	27.6
Silicon	0.47	Glass (7740)	34.8
Platinum	0.54	Silicon thermal grease	46
Tin	0.60	Water	63
Nickel	0.61	Mica	80
Lead-tin solder	0.78	Polyethylene	120
Lead	1.14	Teflon	190
Boron nitride	1.24	Nylon	190
Alumina ceramic	2.13	Silicone rubber	190
Kovar	2.34	Air	2280

or tetrode or the collector of a microwave electron tube is made of metal in the form of a thin-walled cylinder with a top on it. If that metal is part of the vacuum envelope of the tube, it is usually oxygen-free, high-conductivity copper. Heat generated by the sudden stop of electrons on the inner surface of an anode or collector must be transferred to the outer surface before it can be exchanged with another medium. A well-designed collector and electron-beam system will have power distribution over the inside surface as nearly uniform as possible. The temperature rise (or drop) that enables the heat flow through the thin metal wall will depend upon the total area normal to the direction of heat flow, the length of the path in the direction of heat flow, and the thermal resistivity of the material. If the material is copper, its thermal resistivity is 0.11°C-in./W.

The thermal resistance of the anode or beam collector will be given as the product of resistivity and path length divided by surface area. Its units are defined as °C/W. In Fig. 19-1, the thermal resistance of the rectangular segment illustrated is $R \times T/A$. Table 19-1 also lists the thermal resistivities of some commonly used materials. Note that the diamond has the lowest resistivity of all. For this reason, the microscopically small junctions of millimeter-wave solid-state devices such as the IMPATT diode are mounted on diamond heat sinks, which are, in turn, swaged into copper blocks. (Note also that the resistivities of the two most common ultimate heat sinks, water and air, are not low at all. In fact, static air is well known as an excellent thermal insulator.)

The relationship between thermal resistivity and thermal resistance is completely analogous to the relationship between electrical resistivity and electrical resistance. In the thermal equivalent of Ohm's law, temperature difference is the "voltage," thermal resistance is electrical resistance, and rate of heat transfer is the "current." The rate at which heat must be transferred, or power dissipated, is usually fixed. To minimize "voltage-drop," or temperature differential, the thermal resistance of the path must be minimized.

The electrical analogy extends to transient phenomena as well. In pulse-modulated transmitters, power is not continuously dissipated in anodes or collectors. Dissipation can occur during very short intervals that periodically recur. But conduction of heat takes time. When power is dissipated over very short periods, adiabatic heating occurs. In other words, temperature rise depends on the mass of the heated material. What the heated mass is—whether it is inner surface of an anode or collector—depends on diffusion depth, which may be very small. What results is nearly instantaneous heating of the surface to a temperature that may be many times as great as the time-averaged temperature. This is followed by an exponential decay of temperature, analogous to an R-C discharge of an electrical circuit, where the discharge exponent is the thermal time-constant rather than the RC product. However, the temperature rise may not be completely adiabatic. The longer the pulse duration, the greater the chance that some heat will be conducted away while energy is being deposited. This condition leads to lower the end-of-pulse temperature rise for the same pulse-energy dissipation.

Solid-state junctions are especially endangered by transient temperature rise because of their intrinsically small thermal mass. The limiting thermal stress for these devices is usually per-pulse energy for operating duty factors at least up to

10%. Average-power dissipation hardly matters at all. This is why practical, solid-state transmitter components operate at as high a duty factor as possible (with 30% being typical) and with pulse durations as long as possible.

19.3 Heat transfer by free, or natural, convection in air

In the vast majority of heat-transfer situations, the ultimate heat sink will be ambient air. It is cheap, abundant, and will move under its own power. Because hot air is less dense than cool air, it rises when it is heated. This proclivity alone makes air effective as a heat-removal medium. (Static air, as mentioned before, is a good thermal insulator.) Natural air convention is almost something for nothing. However, as Fig. 19-2 shows, air will not only rise along a vertical surface, it will be forced away from it to create a boundary layer. The resulting air-velocity profile in the boundary layer shows that the greater the height of the heat source, the farther away from that surface will be the fastest-moving air. The air at the surface remains practically stagnant. The temperature profile, consequently, will show that surface temperature increases the higher up the measurement is taken.

The rate of heat transfer is given as $Q = h\ A\ \Delta T$, where Q is the rate of heat

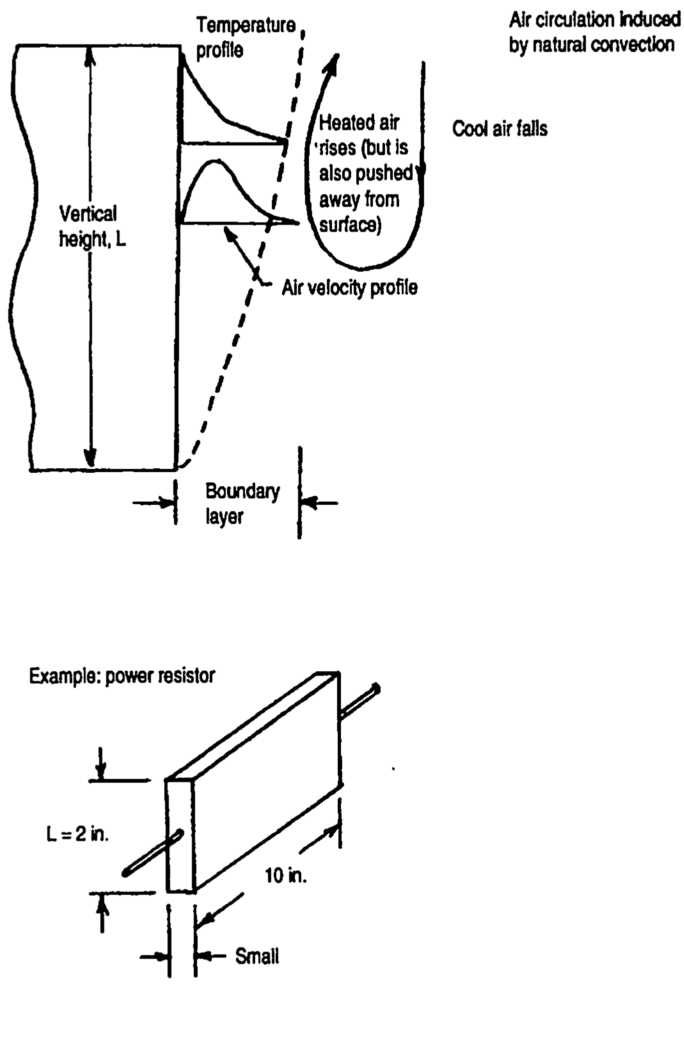


Figure 19-2. Heat transfer by natural convection of air.

transfer in BTU/hour (using the English system of units), h is the convection heat-transfer coefficient in BTU/(ft^2 x °F), A is the surface area of the hot body in square feet; and ΔT is the temperature difference between the surface and the air in degrees Fahrenheit. Note that h is a coefficient. Sometimes it is called the film conductance or the film coefficient, but it is anything but a constant. It will be different for almost every situation and can vary by at least a factor of 5 for the case of free convection of air. In the case of the vertical hot surface, h varies with both ΔT and L, the vertical height of the hot surface, so that $h = 0.27(\Delta T/L)^{0.25}$. This gives

$$Q = 0.27\left(\frac{\Delta T}{L}\right)^{0.25} \times A \times \Delta T = 0.27\frac{\Delta T^{1.25}}{L^{0.25}} \times A\ .$$

If we know power dissipation, or Q, the temperature rise is given as

$$\Delta T^{1.25} = \left(\frac{Q}{0.27A}\right) \times L^{0.25}$$

$$\Delta T = 2.85\left(\frac{Q}{A}\right)^{0.8} \times L^{0.2}\ .$$

Consider the example of the power resistor shown in Fig. 19-2. If it dissipates 20 watts, what will be its average temperature rise? To convert 20 watts into BTU/hour, we multiply it by the conversion factor of 3.41 and get 68.2 BTU/hour (or 34.1 BTU/hour on each side). The area of each side is 10 in. x 2 in., or 20 in.^{2}, or 0.14 ft^2. The height, L, is 2 in., or 0.167 ft. Substituting these values into the equation above, we find that the calculated temperature rise will be

$$\Delta T = 2.85\left(\frac{34.1}{0.14}\right)^{0.8} \times 0.167^{0.2} = 162°\text{F}.$$

Remember, this is *average* temperature rise. The resistor will be hotter at the top than at the bottom.

19.4 Transfer of heat by forced convection of a cooling fluid

For most high-power transmitter equipment, ultimate heat transfer does not result by natural convection of air or water because of their relatively high thermal resistances. In such applications, the natural tendency of a heated fluid to rise must be augmented by external means such as a water pump or an air blower. This forced flow is also confined within tubelike channels, such as the one shown in Fig. 19-3. As in heat transfer by natural convection of air, the rate of heat transfer Q is still the product of h, the heat-transfer coefficient; A, the surface area of the inside of the tube; and ΔT, the temperature difference between

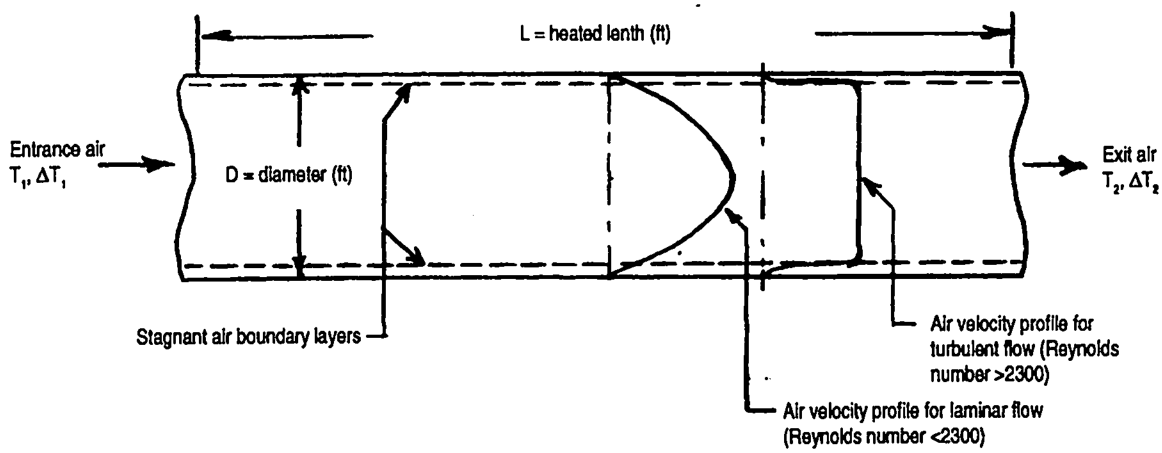


Figure 19-3. Conditions for heat transfer by forced convection of a fluid medium.

the tube's inner surface and that of the fluid. The problem is that the value of h is subject to even more different variables of the system, including tube diameter and fluid velocity, viscosity, specific heat, and thermal conductivity. In addition, not only will the fluid have a higher temperature when it exits the heated length (T_2) than when it enters (T_1), the tube will have a higher temperature at the exit end than at the entrance. There will be not only a T_1 and a T_2 but a ΔT_1 and a ΔT_2 as well. This is handled mathematically by invoking a log-mean temperature difference,

$$\Delta T_M = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}.$$

The value of h depends on the velocity profile of the fluid in the radial direction and the degree of fluid turbulence. The last thing we want is maximum velocity down the center of the tube and stagnant fluid at the surface, the so-called Holland-Tunnel effect. The degree of turbulence in the fluid flow—in other words, a more uniform radial velocity profile—is quantified by the Reynolds number, N_{Re}, which is defined as the product of the tube diameter, D, and the fluid velocity, V, divided by the fluid viscosity, u. The value of h can be extracted from the dimensionless Nusselt number, Nu_m, which is defined as the product of h and tube diameter, D, divided by the thermal conductivity, k. The value of Nu_m depends on the Reynolds number, N_{Re}, and the Prandtl number, Pr_m, which is equal to the product of the specific heat, C_p, and viscosity, u, divided by the thermal conductivity, k.

Figure 19-4 shows how the Nusselt number varies with Reynolds number. The non-abrupt dividing line between laminar and turbulent flow occurs at Reynolds number 2300. For N_{Re} below 2300, Nu_m varies as

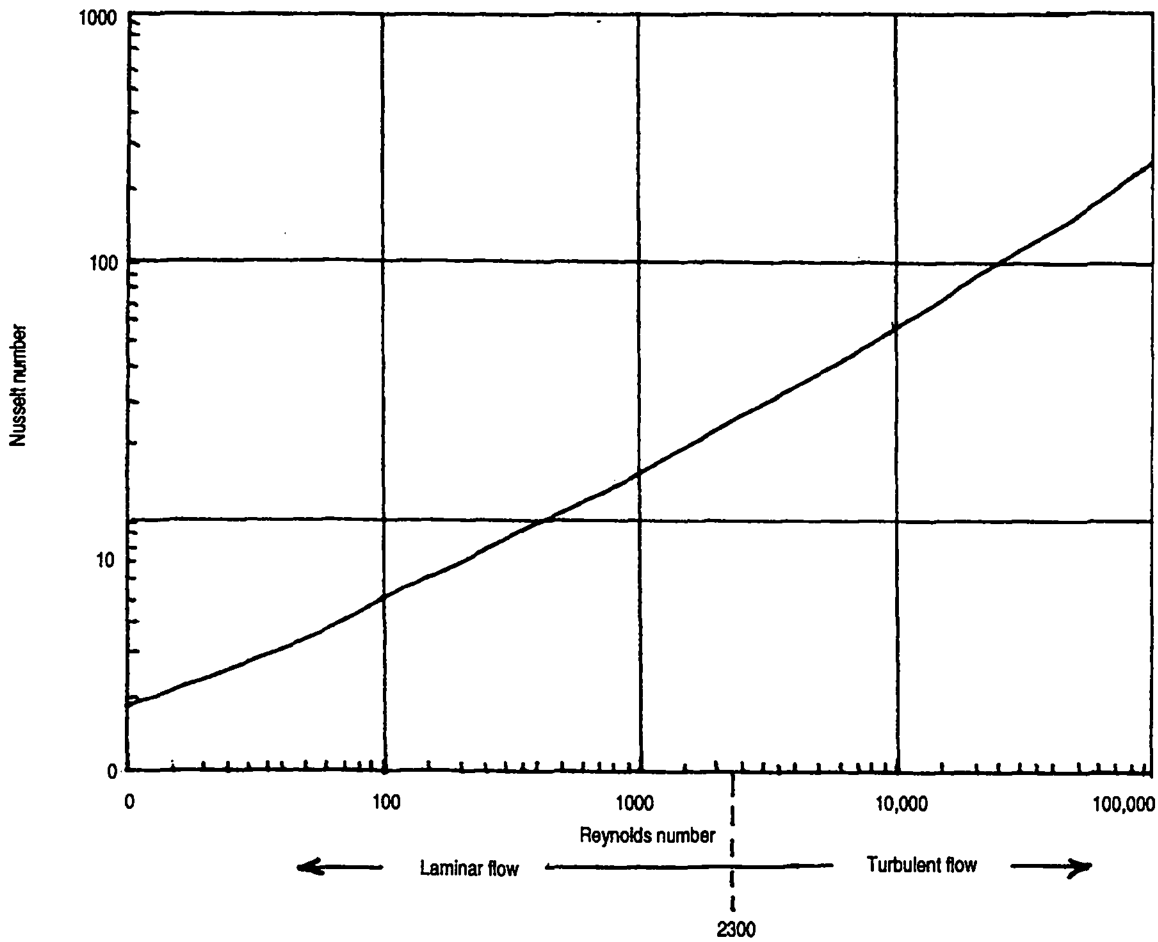


Figure 19-4. How the Nusselt number, which includes the heat-transfer coefficient h, *varies with the Reynolds number.*

$$\sqrt[3]{N_{Re} \times Pr_m \times \frac{D}{L}}.$$

For N_{Re} above 2300, Nu_m varies as $N_{Re}^{0.8}$ x $Pr_m^{0.4}$. As can be easily understood, quantitative analysis of cooling effectiveness depends almost entirely on the determination of h, which in forced-fluid convection can vary by a factor of 40 or so. In general, however, the relative weights of the fluid factors on the heat-transfer coefficient can be expressed as

$$h = 0.23 \times density^{0.8} \times thermal\ conductivity^{0.6}$$
$$\times \left(\frac{specific\ heat}{viscosity}\right)^{0.4} \times \frac{fluid\ velocity^{0.8}}{fluid - channel\ diameter^{0.2}}.$$

19.5. Closed-loop water-cooling systems

Most transmitter engineers are not going to be involved in designs that relate to what has been written so far about thermal management. The devices that must be cooled are already identified, and their cooling requirements are usually specified in terms of air-flow rate as a function of altitude or water-flow rate and water-course pressure drop. Also specified will be the allowable maximum fluid temperature at the inlet—and sometimes minimum inlet temperatures as well. If these external specifications are met, we can be reasonably assured that internal operating temperatures will be in the proper range.

In a forced-flow liquid-cooling system, there is an important quantitative rela-

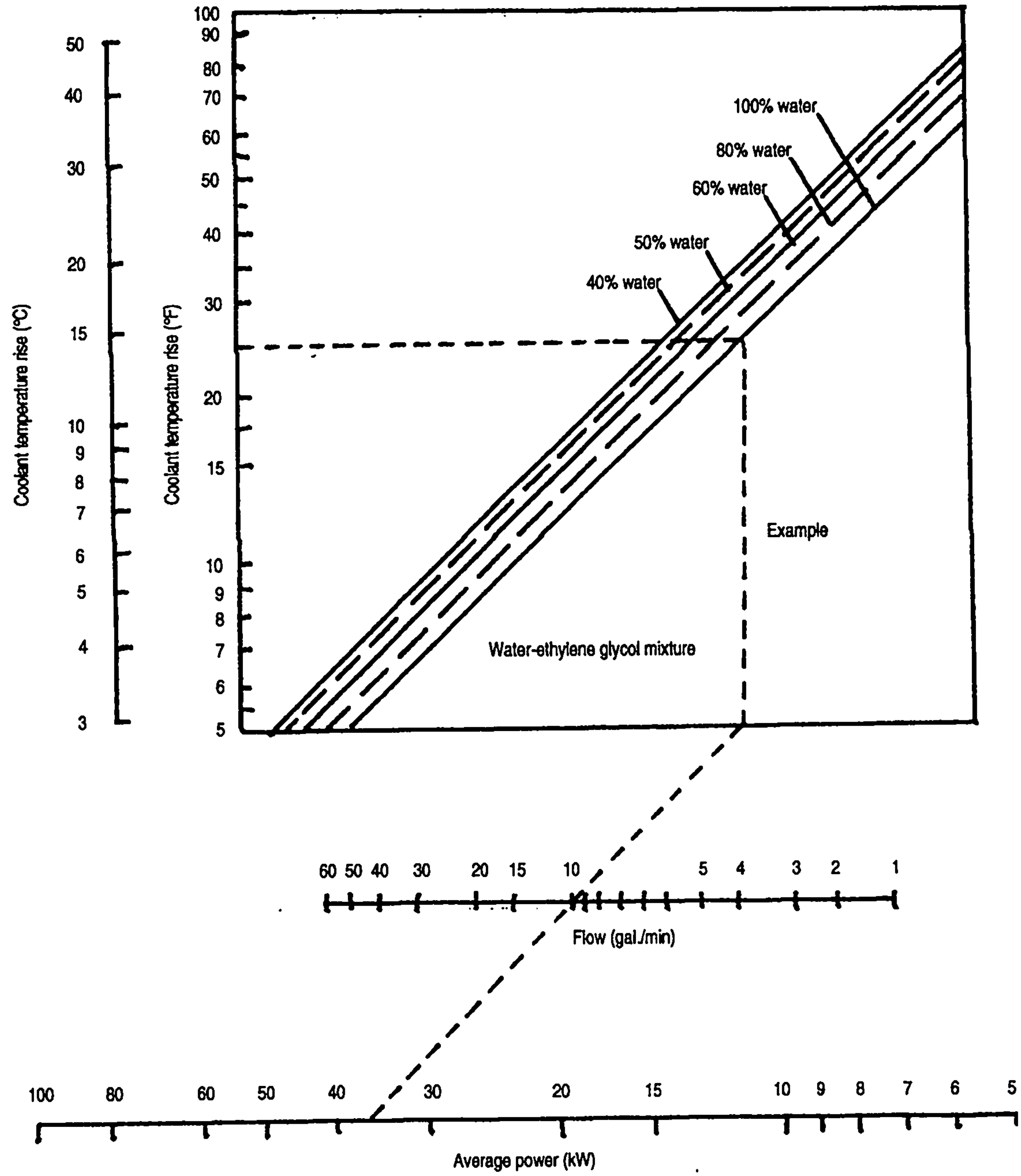


Figure 19-5. Performance of water-cooling system in heat removal.

tionship that most of us are aware of. It is that the heat-transfer rate Q equals the flow rate of the liquid times the density of liquid times the specific heat of liquid times the difference between the outlet liquid temperature and the inlet liquid temperature. For water, the expression reduces to the familiar heat-removal rate, which is expressed in watts and is equal to 264 times the flow rate in gallons per minute times ΔT in degrees Celsius. This is shown in Fig. 19-5 in nomograph form for water and for various concentrations of water and ethylene glycol (antifreeze). This is the basis for estimating anode or collector dissipation by measuring inlet and outlet temperature and flow-rate of the cooling water. In calorimetric RF "dummy" loads, this method is used to measure average input power, which is often transmitter-output power as well.

If air that has been forced through a tube is the cooling fluid, the relationships are more complicated. What matters is the mass of the air that passes through all of the cooling tubes, or channels, of the air-cooled device per unit of time. Typically this is expressed in pounds per minute. Unlike water, however, air is compressible, and its density varies with temperature and barometric pressure. Moreover, what is usually measured is not mass flow, but volumetric flow, such as gal./min for water or ft^3/min for air. The heat-transfer rate for air, which is comparable to the expression given above for water, is

$$Q = watts = \frac{164 \times flow\ rate\left(\frac{\text{ft}^3}{\text{min}}\right) \times \Delta T(^\circ\text{C})}{inlet\ temperature(\text{K})}$$

at 1 atmosphere (29.92 in. of mercury). When the expression is evaluated at, say, an air-inlet temperature of 55°C, the absolute temperature is 328 K and the heat-transfer equation reduces to Q = watts = 0.5 x flow-rate (ft^3/min) x ΔT (°C). As inlet air temperature increases, air density decreases and mass flow decreases as well. If the altitude is higher than sea level, the density must be adjusted for that factor too. At any temperature or pressure, air density (expressed in lb/ft^3) will be 0.737 times atmospheric pressure (in inches of mercury) divided by absolute temperature (in kelvins).

Most air-cooled vacuum tubes have an upper temperature limit of 250°C. It is usually measured at the core of the "radiator" (more properly named the "forced-convector"), which is attached to the anode or collector of the device. Characteristic curves are usually supplied by the manufacturer indicating the required air-volume flows in ft^3/min for varying anode power dissipation. Also, in order that an appropriate air blower can be specified, the tube maker includes pressure-drop data through the cooling channels as a function of flow rate.

What neither of the relationships given above suggests, however, is how hot the inside surfaces of the anode or collector—or the dummy load, for that matter—will get. The ΔT used in this case is parallel to the cooling flow, or end to end. In Fig. 19-3, if L represented the entire length of the cooling path, ΔT would be T_2 - T_1. What is not revealed is the ΔT perpendicular to the cooling flow, which represents the temperature rise from fluid boundary to heated surface,

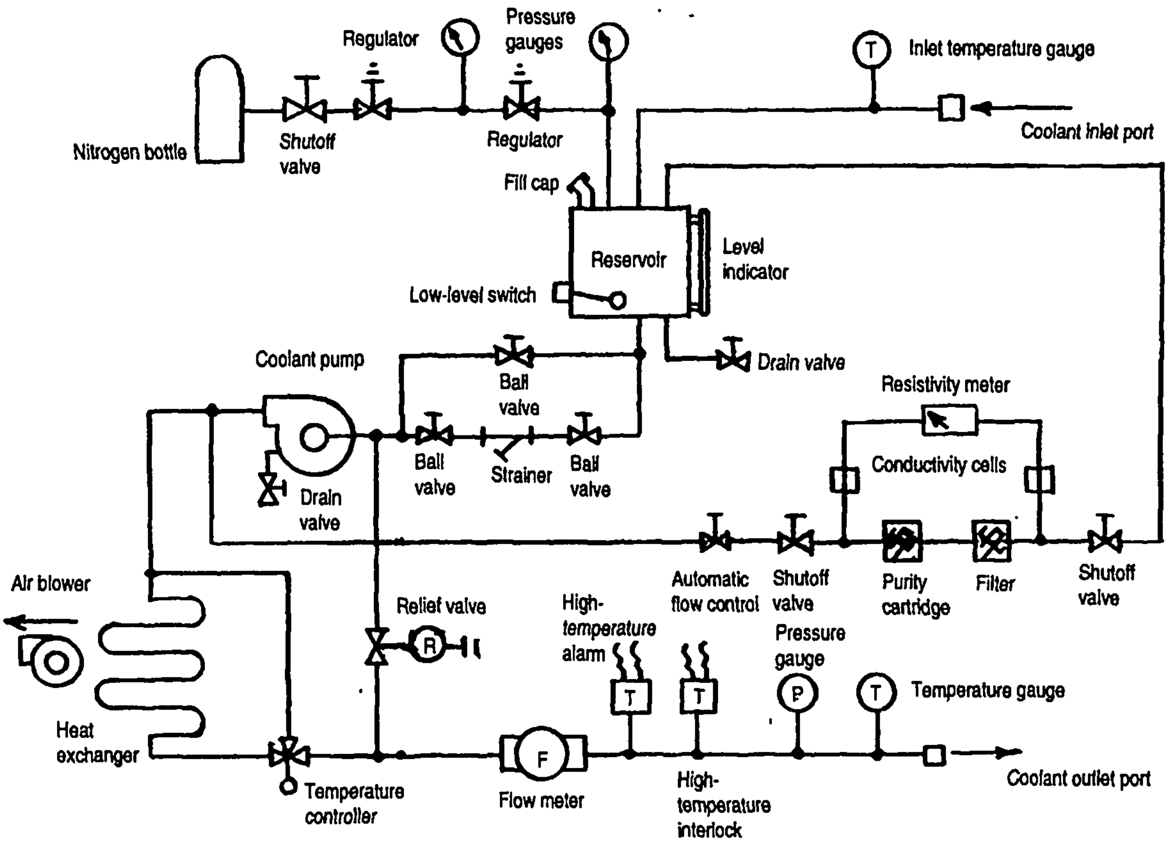


Figure 19-6. Components of a typical closed-loop, high-purity water-cooling system.

part of which is the log-mean ΔT described earlier. The total temperature rise is determined by the total thermal resistance of the heat-flow path, which is essentially transverse to the flow of liquid coolant.

A closed-loop water-cooling system for a high-power transmitter resembles in many ways the cooling system for a car engine. The major components of such a system are shown in Fig. 19-6. One of the key components is the pump, which provides the pressure head that enables the forced flow of coolant. (Although the liquid coolant could circulate through the system by natural convection from low point to high point and back, it will do so at too leisurely a pace.) Other key components include the heat exchanger, which accomplishes the second and ultimate level of convective heat transfer from liquid to ambient air, and the blower, which provides the forced flow of air through the heat-exchanger coils. Where there is an abundant source of ambient water, such as on board a ship or near a coastline or lake, water-to-water heat exchangers are often used. These are capable of heat transfer at lower ΔT and usually to a heat sink (the ambient water) that has a lower temperature than that of the ambient air. The disadvantage of the water-to-water exchanger is the very real possibility of leaks between the two water paths. A mandatory requirement for the water (or alternative liquid coolant) in the closed-loop primary path is that it be high-purity, de-ionized, and oxygen-free. Any leak from the secondary side of the exchanger, even if the larger pieces of flotsam have been filtered out, will make short work of polluting the primary side.

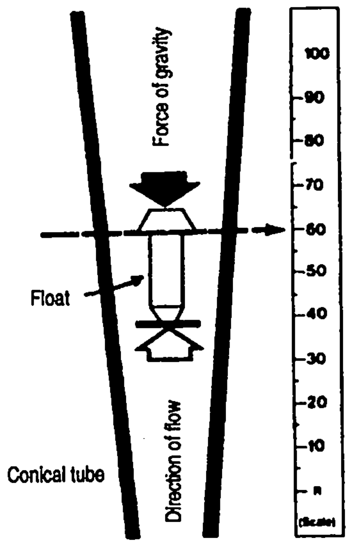
In the interest of maintaining the purity of the primary-loop coolant, a purity-maintenance loop usually shunts the main flow path. Included in its flow path are mineral-bed purity cartridges and submicron particle filters. The purity of the water is usually monitored by measuring its electrical resistivity. This function is carried out by the resistivity meter, which is shown shunting the conductivity cells. High-purity water has a resistivity typically greater than 1 megohm-cm, although marginal performance is obtained with resistivity as low as 300 kilohm-cm.

The cooling paths of most microwave-tube transmitters do not include loads that may operate at high voltages with respect to ground. The anodes of large hard-tube-modulator switches may undergo large pulsed-voltage swings, however; and the anodes of electronic voltage-regulator series tubes will also be at high voltage with respect to ground. In these cases not only is water resistivity important, but the length and diameter of the water columns leading to and from the water-cooling jackets are important too. The combination of the three will determine the electrical resistance of the water path and the amount of electrical current that will flow through it. Such current can produce electrolysis effects in the water. Needless to say, the water conduits must also be non-conducting. Standard polyvinyl chloride (PVC) pipe or, to be safe, chlorinated PVC (CPVC) pipe is very useful in this application. Where high flow rate dictates large-diameter pipe, the length of the water column must be proportionately long. Before PVC pipe became a useful alternative, and where high voltage was also involved, porcelain-ceramic water-columns in the shape of cylindrical coils were almost standard water-system components. Today, square-sided coils are often fashioned from short straight sections of PVC pipe and 90° plumbing elbows, thus allowing a long flow path to be coiled up in a relatively compact volume.

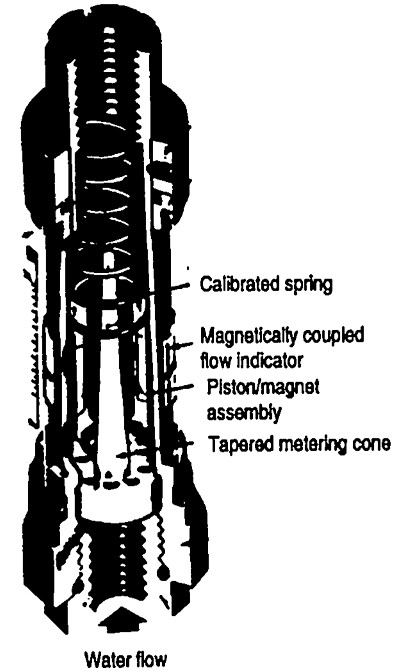
The materials used in a high-purity water loop should be restricted to copper, bronze, brass, stainless steel, and plastic, like the PVC pipe. No ferromagnetic materials should ever be used. The other important feature, and one not likely to be found in an automobile cooling system, is the nitrogen-gas blanket, which is intended to replace the air in the unfilled volume at the top of the liquid reservoir. The remaining components are self-explanatory: interlock switches, temperature and flow gauges, flow-adjusting valves and shut-off valves, reservoir liquid-level indicator, and pressure regulators and gauges.

The one condition throughout the cooling system that needs to be interlocked with the electrical control of the transmitter is water flow. Several kinds of different flow meters and flow-interlock electrical switches are available for this purpose, as illustrated in Fig. 19-7. The prototype of all of them is the classic variable-area flow meter illustrated in Fig. 19-7a. Called a Rotameter, it uses a float that is suspended in a conical-shaped glass pipe by the flow of liquid. The greater the flow, the higher up the pipe the float will be suspended. A feature on the float allows it to be compared with a scale, which may be either external or etched on the glass. Needless to say, the Rotameter only works when it is vertically oriented.

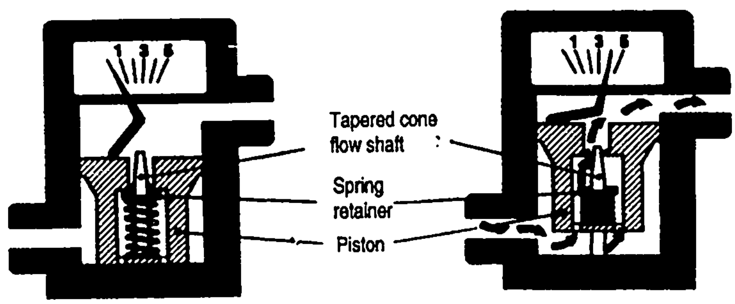
A spring-loaded version of the Rotameter (Fig. 19-7b) uses constant-diameter pipe, but its metering cone is tapered with its diameter decreasing along the direction of flow. Liquid, entering through holes in the slug that holds the meter-



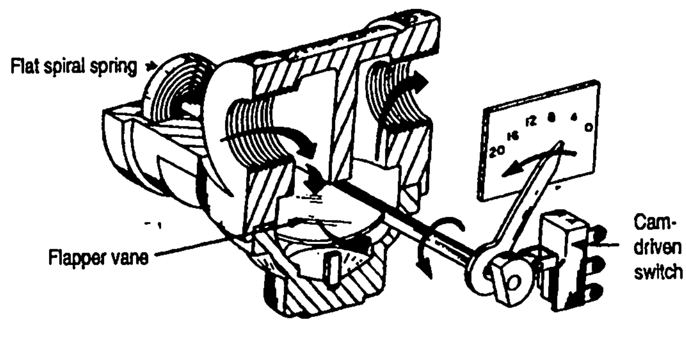
A. Classical variable-area flow meter (Rotameter); must be vertically oriented



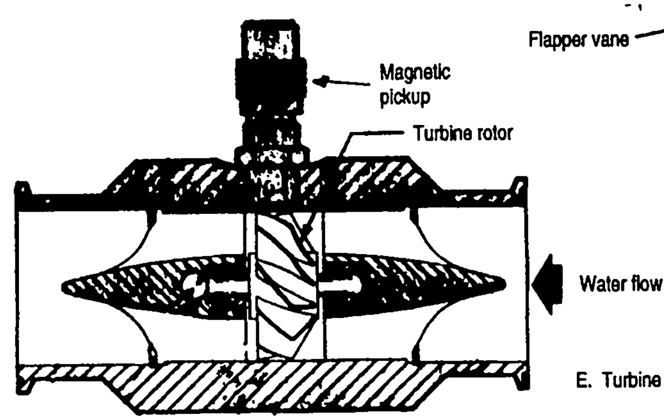
B. Practical spring-loaded Rotameter (orientation insensitive)



C. Piston-type variable-area flow meter and flow switch



D. Vane type variable-area flow meter



E. Turbine flow meter

Figure 19-7. Types of liquid flow meters and flow-interlock switches.

ing cone, applies pressure on an annular piston whose motion is opposed by a calibrated spring. The greater the flow, the greater the area required between the inside of the piston and the outside of the metering cone for positional equilibrium, meaning that the piston must move along the direction of flow. The movement of the piston can be magnetically coupled to an external annular follower whose position can be related to flow by a longitudinal scale. The magnetically coupled follower can also be used to actuate a small electrical switch, whose longitudinal position can be adjusted to give an electrical indication of whether flow is above or below a preset threshold.

Another piston-type, spring-loaded, variable-area flow meter (Fig. 19-7c) can be configured to directly drive a meter needle and/or an electrical interlock switch. The vane-type variable-area flow meter (Fig. 19-7d) uses a semi-circular vane in a not-quite hemispherical chamber to achieve variable-area performance against a flat-spiral spring. The resultant deflection is rotational, which can be compared with a calibrated meter scale and operate an electrical interlock switch through a cam, as shown.

The turbine-type flow meter (Fig. 19-7e) is probably the most inherently accurate, but it is also the most expensive. In it, liquid flow causes a turbine to rotate, as flowing gas does in a jet engine. The turbine's angular velocity is indicated by a magnetically coupled response to the passage of each rotor-blade tip past a magnetic pickup, giving a variable-frequency pulse-train electrical output. The frequency, or course, is proportional to flow rate.

Such flow meters and interlock switches are usually deployed in the return lines of each coolant path. (It does not matter how much liquid starts out in a cooling path, only how much comes back.) A typical water manifold for a dual-klystron RF power source is shown in Fig. 19-8. The main water-flow path, whose flow rate is 47.5 gal./min, is directed to the collectors of the two klystrons. Water flow is connected to the collectors in cascade, or series, because of their relatively low individual pressure drops. A separate path cools the body of each klystron because of relatively high pressure drop at the 2.6 gal./min flow rate. A third parallel path, also 2.6 gal./min, cools the focus electromagnets of the two klystrons. They too are connected in cascade. The four return paths each have separate temperature gauges, electrical temperature-interlock switches, integrated flow meters, and interlock switches. Total supply pressure and return pressure are also metered. Check valves in the lower flow paths prevent backflow when those water courses are drained.

19.6 Vapor-phase cooling, or convection with state change

Water boils at 100°C. In so doing, it changes state from a liquid to a vapor called steam. To accomplish this change of state, even at constant 100°C, it must absorb a considerable amount of energy known as the latent heat of vaporization, which is 540 joules per gram of water. While water is in the liquid state, it takes one joule of energy to raise its temperature one degree Celsius. The usual outlet-inlet temperature differential for a closed-loop, forced-convection water-cooling system is in the range of 30°C to 40°C. A temperature of 70°C is typically considered a maximum outlet temperature because it is low enough to preclude spot-boiling within a water course, which can reduce the heat-transfer effective-

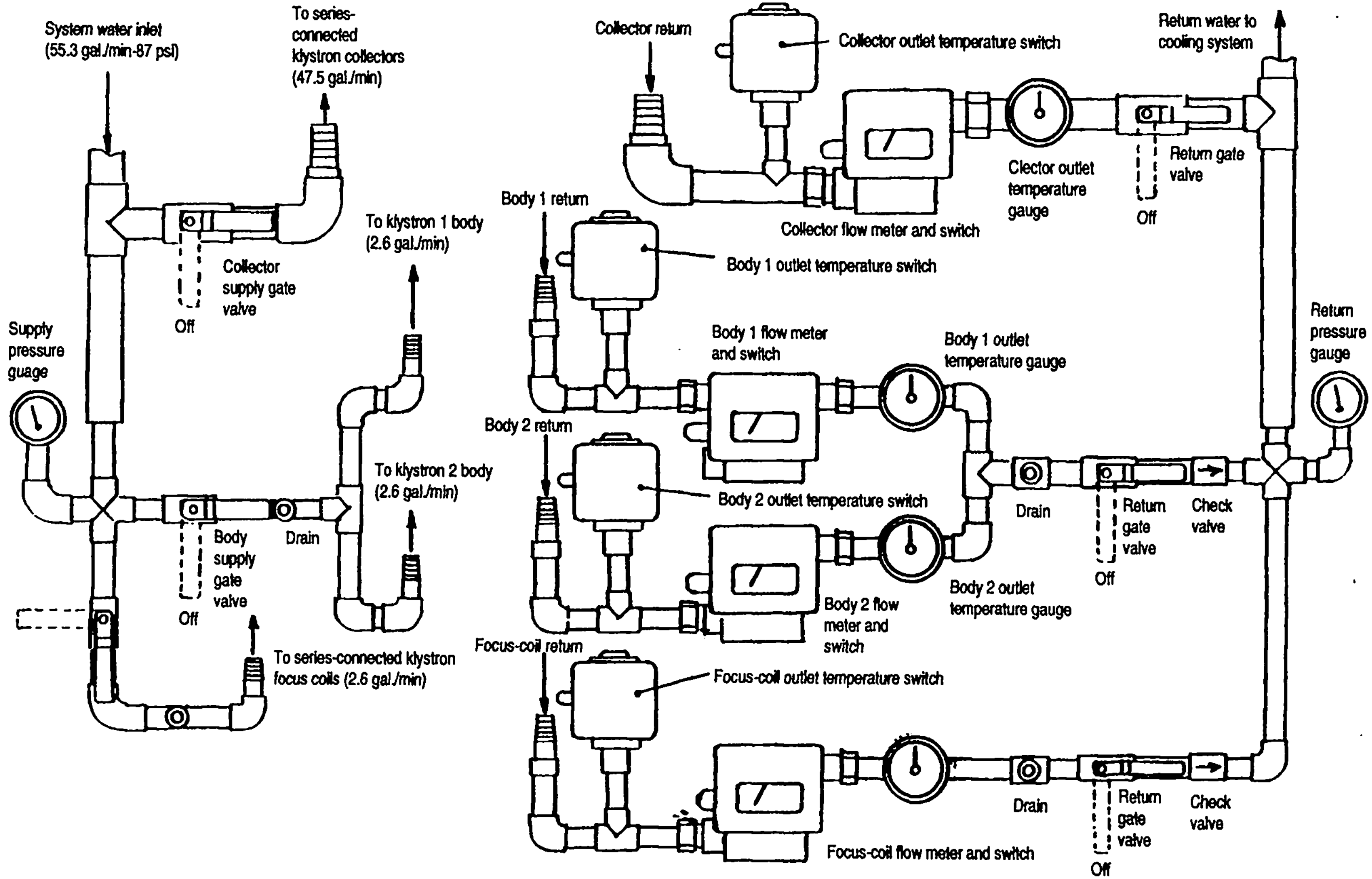


Figure 19-8. Typical water manifold arrangement for a dual-klystron amplifier system.

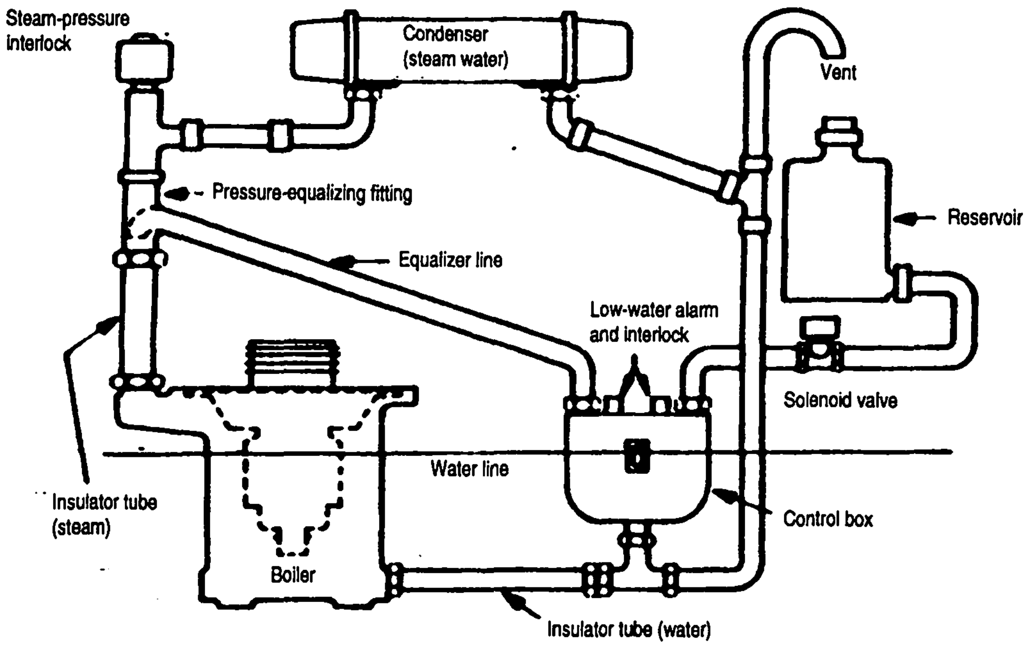


Figure 19-9. Components of a vapor-phase cooling system for high-power vacuum tubes.

ness at the surface, especially if the flow rate is marginal. This means that each gram of water is responsible for removing between 30 and 40 joules of energy, compared with 540 joules removed for each gram of water if it is allowed to be converted into steam. Energy is not power, however, and we are interested in the *rate* at which energy can be removed, which is characterized in terms of power density. By forcing water through the cooling channels, high mass flow can be obtained (as well as the desired attributes of turbulent flow). If each gram of water can take away 30 to 40 joules of energy, and we move a lot of grams past a given point per unit of time, the power density can be quite great, typically 1000 W/cm^2 of internal anode (or collector) surface. By contrast, the power density of a closed-loop vapor-phase cooling system, which is powered by natural convection, can be at maximum 135 W/cm^2 of internal anode surface.

This is still pretty good, considering that a vapor-phase system, such as the one shown in Fig. 19-9, can be much simpler than a closed-loop, pump-driven water-cooling system. And it uses a lot less water. Primary heat transfer takes place in the boiler, into which the anode or beam collector of a tube is inserted and sealed so that the system will be vapor-tight. The tube's anode and boiler axes must be vertical, and the water level must be as shown. The function of the control box, which acts as a manometer in that the water level in it should be the same as that in the boiler, is to maintain the proper water level. It does so by opening the solenoid-operated valve to let make-up water into the control box from the reservoir as needed. If this does not do the job, or does not do it rapidly enough, the low-water alarm and the electrical interlock will signal the transmitter power source to shut down. An equalizer line, connected between the boiler steam outlet pipe and a comparable outlet port on the control box, makes sure that the steam vapor pressure is the same at the top of the control box as it is at the top of the boiler. The steam gives up the latent heat of vaporization that it

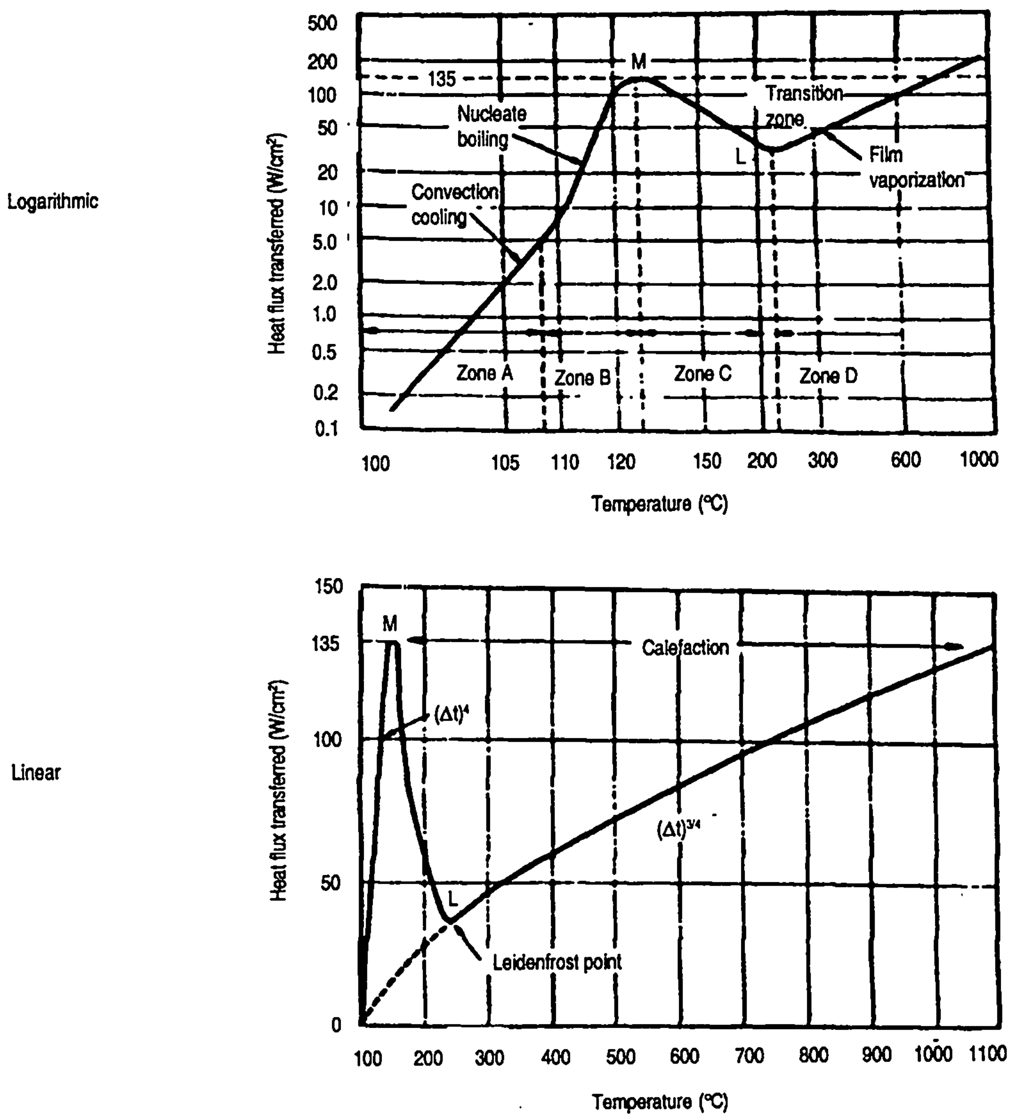


Figure 19-10. Temperature characteristics of vapor-phase cooling system.

has accumulated to either ambient air or secondary cooling water in the condenser. Then it reverts to the liquid state and rejoins the system at the water-inlet side to repeat the process.

The graphs in Fig. 19-10 show the same information, but in linear coordinates on the bottom and in logarithmic on the top. What both illustrate is the critical temperature dependence of the heat-transfer power-density performance. The maximum of 135 W/cm^2 is achieved at the critical temperature of about 125°C. The temperature condition at this point or just below it is called nucleate boiling, which is characterized by individual bubbles of steam that break away from the heated surface and rise through the surrounding water, carrying their heat of vaporization with them. If the temperature is allowed to get higher, a phenomenon called calefaction takes place. Here, individual bubbles merge increasingly into a sheath of steam at the heated surface. These bubbles begin to thermally insulate the surface from the surrounding water. The heat-transfer effectiveness steadily deteriorates with rising temperature until the Leidenfrost point is reached.

Here, the vapor sheath is complete, and all heat transfer takes place through it. If the power-dissipation density in the heated surface is not reduced from its 135 W/cm^2 value, the temperature at the surface will rise to 1000°C, which obviously must be avoided.

Avoidance strategies employed in the design of the outside surfaces of vapor-cooled anodes or beam collectors tend to call for thick radial fins. The radial dimension of these fins permits a radial temperature gradient as well. If this gradient straddles the 125°C optimum point—hotter at the root and cooler at the tip—the average heat-transfer performance will be less than the maximum achievable if temperature were everywhere constant, but it will be self-correcting. A hot spot at a fin root will push the heat-transfer performance there further away from the maximum point, but will pull the temperature at the fin tip up, pulling its performance closer to the maximum. Needless to say, the external area of the heated surface will be greater than the internal.

The condenser in the vapor-phase system is more efficient in secondary heat transfer than the heat exchanger in a water-cooled system because of the more advantageous temperature difference. Steam and steam that has condensed back to water are both at 100°C. If the heat is transferred to ambient air at 25°C, ΔT is 75°C. A water-cooling system with a 30°C water-temperature rise and a maximum outlet temperature of 70°C has an inlet temperature of 40°C. The average water temperature in the heat exchanger will be 55°C, giving a ΔT of 30°C with ambient air at 25°C. The steam-water condenser will have something like 2.5 times the temperature-difference of the water heat exchanger. Furthermore, it can be built smaller, lighter, and cheaper. And because water flow in a vapor-phase system is accomplished automatically by what is called thermosyphoning, these systems operate with little or no acoustic noise, which can sometimes be important. Pump-driven, water-cooled systems can never be called quiet. Nor can blower-driven air-cooling systems (especially if they operate at 400 Hz primary power).

19.7 Multi-phase cooling

The most modern high-power tubes are now being cooled with hybrid systems that use a combination of vapor-phase and high-flow-rate water cooling. These systems are generically called multi-phase cooling. A trade name for such a system is Hypervapotron. Multi-phase cooling is characterized by surface vaporization of water into steam bubbles that are then almost immediately condensed back to water by the rapidly flowing surrounding water. The external cooling characteristics of this system are largely indistinguishable from conventional water-cooled tubes, except that its pressure drop is likely to be considerably less than a conventional system for comparable flow rate.