amateur service newsletter
W6SAI

Forced-Air Cooling of Transmitting Tubes

Some Considerations in the Selection of a Suitable Impeller

BY WILLIAM I. ORR,* W6SAI

We live at the bottom of a vast ocean of air. This invisible, life-supporting elixir provides the equipment designer with an inexpensive and efficient cooling medium for heat-generating devices, such as transmitters and receivers. Over the years, electronic equipment has grown more sophisticated and compact, and the problem of removing heat from the gear has become acute. Until someone miniaturizes the watt, heat-exchange systems will remain one of the major problem areas of equipment design. Aspects of forced-air cooling systems are discussed in this article.

Most electronic equipment generates heat, and this heat must be removed or the equipment will eventually burn up. The heat may be removed by radiation, conduction or convection [1], or by a combination of these methods. This article examines forced-air cooled systems (an efficient form of convection cooling), which are used in commercial transmitting equipments up to the level of tens of kilowatts and, in amateur gear, up to the so-called "two-kilowatt p.e.p." level. Generally speaking, from 20 to 70 per cent of the primary power drain of electronic equipment is dissipated in heat emitted from tubes and components, and the resulting temperature rise must be held within reasonable limits to insure satisfactory life for both the tubes and the other parts in the equipment.

The Air System

Two typical forced-air cooling systems for a power tube are shown in Figs. 1A and 1B. They consist of an air blower, or impeller; a conduit to guide the cooling air to the tube, or a pressurized chassis; the heat radiator of the tube; and an air exhaust exit. By stretching the imagination only a little, this air system can be compared to the electrical series circuit of Fig. 1C, in which each component in the air system is represented by a resistor which has a potential drop across it corresponding to the *back pressure* or resistance [2] that the original component offers to the flow of air. The sum of the back pressures in the air system must add up to the total pressure of air supplied by the blower, just as the sum of these voltage drops in the electrical analogy must add up to the generator voltage. The blower in the air system corresponds to the generator in the electrical system, of course.

The electrical analogy suffers in that the back pressure across a component in the air system does not strictly follow an equivalent of Ohm's Law for electric potential drops. Instead, the

* Manager, Amateur Service Dept. Eimac, Division of Varian, San Carlos, California 94070

1 Quinn, "The Stanley Steamer," *QST*, May, 1966.

2 The resistance offered to the flow of air may also be expressed in terms of "pressure drop" or "static pressure."

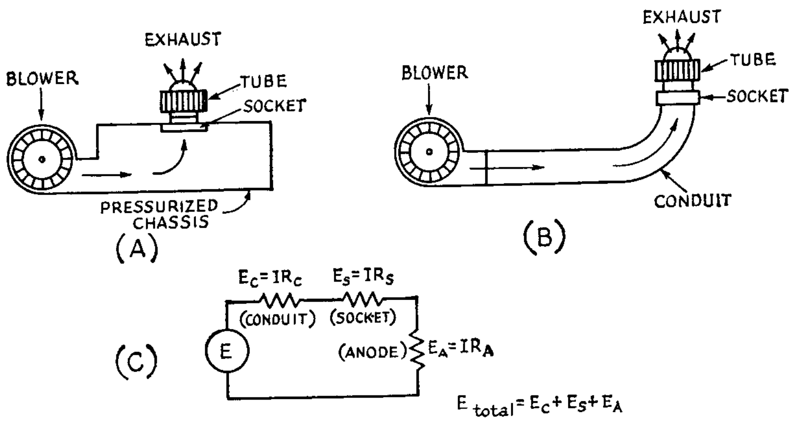

Fig. 1—A forced-air cooling system. In A, the blower is mounted directly on the chassis which is used as a plenum chamber. Air is exhausted past filament and plate seals of the tube. In B, the blower is mounted at some distance from the tube, and cooling air is conducted to the tube via a conduit or hose. C indicates an electrical analogy of the forced-air system. The blower is represented by generator *E*, and various unavoidable back pressures are represented by voltage drops across resistors *Rc* and *Rs*. Useful work (cooling the anode) is represented by voltage drop (E_A) across the tube.

back pressure across an air-system component varies approximately as the *square* of the air-flow rate (volume per unit of time). Thus, if the volume demand is doubled, about four times the pressure will be necessary to meet the increased requirement. Even though the analogy is inexact, the transmitter designer who is comfortable in the presence of Ohm's Law for series circuits can gain insight of the action of pressure drops incurred in a forced-air cooling system.

The problem to be solved is that of determining the size and characteristics of an air blower that will satisfy the temperature limitations imposed upon a particular tube type by the manufacturer, and reconciling these limits with available blowers. Maximum operating temperatures and air requirements of forced air cooled transmitting tubes are generally supplied in the data sheet, or provided upon request by the tube manufacturer. This simplifies the problem considerably, as few engineers have the equipment or time to run temperature checks on transmitting tubes. Blower data, too, is supplied by the numerous impeller manufacturers. It remains, then, to translate this available and unfamiliar data into the proper hardware for the system at hand.

Tube Cooling Requirements

Forced-air-cooled transmitting tubes, such as the 4CX250B, 4CX1000A and similar external-anode tubes, require cooling air to be passed from base to anode[3]. Unless otherwise specified in the data sheet, cooling air should flow as long as the tube filaments are lighted. The external anode cooler of tubes of this family is usually composed of a number of copper fins arranged in a circle about the anode core, with the air passing vertically across the surface of the fins. An exchange of heat takes place between the fins and the passing air, the moving air extracting heat from the anode core and holding overall anode temperature at or below the maximum limit. As the air is impeded in its flow through the interstices of the anode structure, a back pressure is created, caused by friction of the air against the fin surfaces, and by turbulence of the air in the anode passages.

The cooling airflow requirement for transmitting tubes may be expressed in terms of the ratio of watts of anode dissipation to tube temperature (in watts per degree Centigrade) as a function of either the mass airflow rate in pounds of air per minute, or the volumetric airflow rate in cubic feet per minute[4]. This information may be expressed in graphic form (Fig. 2), enabling the design engineer to determine the actual cooling-air requirement in terms of specific tube temperature and system back pressure.

[3] Large convection- and radiation-cooled glass tubes (4-400A and 4-1000A, for example) also require forced-air cooling to hold seal temperatures within prescribed limits.

[4] Precise calculation of airflow in cubic feet per minute must take into account air humidity and barometric pressure. Equipment builders often design for a mythical user living in Denver, Colo., who operates the equipment on a hot, humid day.

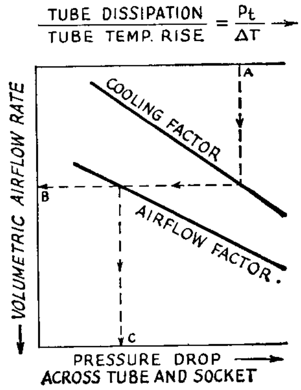

Fig. 2—Allowable temperature rise and dissipation (A) of power tube determine airflow rate (B) from laboratory measurements. Pressure drop (C) across the tube and socket may be measured by a manometer device. The interlocking relationship of cooling requirements may be expressed in graphical form, as shown here.

The total heat to be removed is determined from a study of the operating characteristics of the tube, and includes plate and filament dissipation (plus grid and screen dissipation where applicable). Maximum element dissipation rating is normally given in the data sheet. The operating temperature rise of the tube is found by taking the difference between the maximum measured tube temperature (at the hottest point of the tube) and the maximum inlet air temperature expected. The air requirements expressed by the plots of the cooling factor and the airflow factor are usually given as a pressure drop across the *tube and socket* expressed in *inches of water*, and a corresponding volumetric airflow is defined in *cubic feet per minute* (c.f.m.). This information is necessary to determine the size and speed of the blower required to provide the proper airflow through the system. Volumetric air flow may be calculated or determined by experimental means.

Air-Pressure Measurements

Air pressure in a forced air system may be defined in terms of an equivalent weight of water.

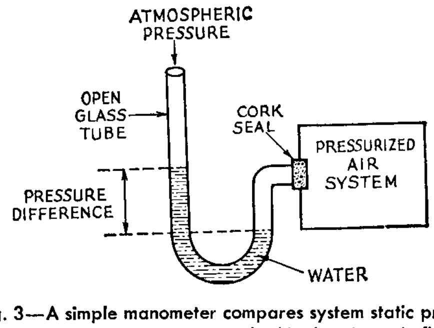

Fig. 3—A simple manometer compares system static pressure with atmospheric pressure. In this drawing, air flows at right angles to manometer input, i.e., into or out of this page. Pressure difference is expressed in "inches of water." Placement of manometer to avoid turbulence in the system should be determined by experiment.

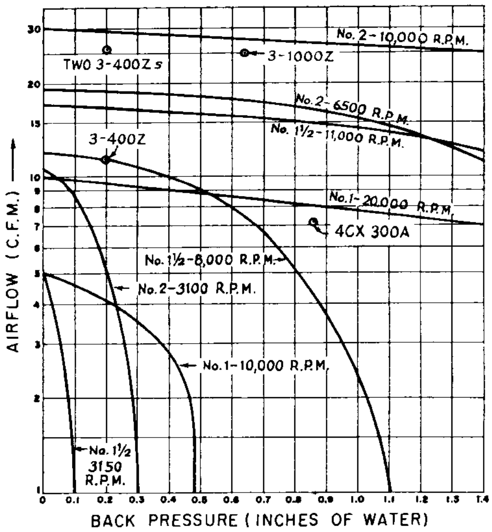

Fig. 4—Typical performance data for No. 1, No. 1½, and No. 2 centrifugal blowers. Performance of blowers of different sizes and speeds can be compared with the cooling requirements specified for various tube types. Notice that requirement points are shown for a pair of 3-400Zs as well as for a single tube. If the requirement point falls on or below the performance curve for a particular blower, that blower will give adequate cooling under the conditions outlined in the text. The curves show that blower efficiency drops rapidly after a critical value of back pressure is reached, and that the blower "windmills" (reaches zero output) at high values of back pressure. High-speed blowers can withstand more back pressure than can low-speed units (notice the curves for 10,000- and 20,000-r.p.m. blowers.

(The weight of a uniform column of water 27.7 inches high is 1 lb. per square inch of column base area.) The measurement is made by means of a *manometer* whose readings are expressed in inches of water (Fig. 3). A simple manometer for shop use may be constructed of a short length of ¼-inch glass tubing bent into a U shape, with one end left open to the atmosphere. The opposite end is inserted in the air system in proximity to the tube socket and *at right angles* to the airflow. Optimum position should be determined by experiment so as to make sure that the manometer is not influenced by eddy currents in the airstream. The bottom portion of the manometer is filled with water and, if the air pressure in the cooling system is equal to atmospheric pressure, the water will rest at equal heights in both vertical sections of tube. Under this quiescent condition, no air moves through the system or, if it moves, it encounters no back pressure. However, if a difference of pressure between the atmosphere and the inclosed air system is created by a blower, the water will be forced up towards the open end of the glass tube by the back pressure of the air moving through the system. The pressure within the duct or plenum, as compared to atmospheric pressure, may be noted by measuring the difference in height (in inches) of the two water columns, as shown in the illustration.

System Pressure Drops

Pressure drop in an air system is caused by physical obstruction to the flow of air, or by turbulence in the air. In the case of a tube anode which contains many fins over which the air must pass, the pressure drop is intentional and useful. Other system drops caused by air friction, pressure drops in the hose or socket, or a change in the air velocity in the system, are undesirable and not useful. All pressure drops caused by these factors must be added to the pressure drop of the tube and socket. Drops caused by an abrupt change in the cross-sectional area of a system include *both* expansion and contraction drops for variations in conduit area, and are additive. While these values may be calculated for a system of known dimensions, it is beyond the scope of this article to cover such calculations. Suffice to say that when the overall pressure-drop and airflow requirements are determined, it is possible to match the requirements to the blower characteristics to achieve satisfactory system cooling.

Blower Characteristics

Air blowers come in many shapes and sizes and some are "good" and some are "poor." The most commonly used impellers in air cooled systems are *squirrel-cage (centrifugal) blowers*, and *axial fans.* The important characteristics of an air cooling system are the relationship between blower-outlet back pressure (in inches of water) and the airflow (in cubic feet per minute), and these characteristics determine the blower to be used. It is foolhardy to determine the "good" air impellers from the "poor" impellers by intuition.

Graphs of typical squirrel-cage blower performance for various units are given in Figs. 4, 5 and 6. The areas under the curves are regions in which the blower does useful work. It can be seen that as the back pressure rises, the efficiency of the blower decreases until, at some critical value of back pressure, the blower ceases to function as a useful device and merely "wind mills" the air about the impeller blades and cavity. This is termed "blower cutoff." Blowers vary to a great degree in their ability to cope with back pressure: low speed, open axial fans are the least efficient, while high speed squirrel-cage devices have somewhat higher efficiency.

Squirrel Cages and Axial Fans

The typical squirrel-cage blower has a multi-bladed impeller wheel rotating within a tightly fitting housing.[5] Small units normally have the discharge edge of the blade inclined forward, in the direction of rotation. The inexpensive axial fan, on the other hand, has a few, large, wide blades (usually four), slowly rotating in the open air or in a short housing section. More expensive vane-axial impellers have more blades (five or six) and rotate at higher speeds.

[5] The most efficient centrifugal blowers have a housing which closely fits the edges of the rotor. Excessive air gap between the rotor and the rim of the housing destroys the ability of the blower to work into back pressure.

Squirrel-cage blowers are often cataloged according to impeller wheel diameter and rotational speed. Thus a No. 2½ blower has a wheel diameter of 2½ inches, and may be available in a number of speeds, of which 2800, 3100, 6000 and 9000 r.p.m. are common off-the-shelf values. For a given wheel size and design, the c.f.m. delivered is proportional to blower speed, as is the ability to withstand system back pressure. Using the electrical analogy again, it may be said that the "voltage regulation under load" (ability to overcome back pressure) of any blower increases as the impeller speed increases. Unfortunately, as the impeller speed increases, the air noise, motor noise, vibration and unit cost also increase. While a 2800-r.p.m., or even a 6000-r.p.m. squirrel-cage blower may have a tolerable noise level, many 15,000-r.p.m. blowers create sufficient air noise to deafen even the most dedicated DX-contest operator.

Examination of the blower curves shows that a "trade-off" exists between rotational speed and wheel diameter and, generally speaking, a large impeller wheel running at moderate speed will be more satisfactory and less noisy than a smaller wheel running at a somewhat higher speed.

Inexpensive axial fans deliver large volumes of air at rather low rotational speeds and are generally fairly quiet, but suffer more than do squirrel-cage blowers from the effects of back pressure (Fig. 7). *Most small, low-speed axial fans and squirrel-cage blowers cannot move sufficient air into moderate values of back pressure to properly cool modern external-anode transmitting tubes, and their use should be tempered with caution.*

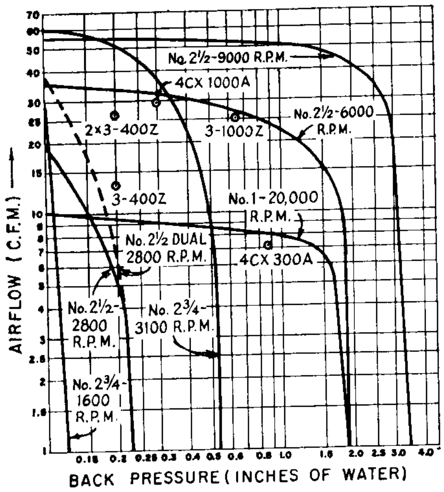

Fig. 5—Typical performance curves, similar to those of Fig. 4, for No. 2½, No. 2¾, and dual No. 2½ blowers. Notice that the No. 2½ 6000-r.p.m. blower will handle the cooling requirements of all of the tube types indicated, since the requirement points fall below the curve for this blower. "Wind-milling" is clearly indicated by the rapid drop of airflow to an unacceptable rate at the higher values of back pressure. Also notice that the use of dual blowers provides more airflow than a single blower of the same type at low back pressures, but does not project the "wind-milling" point.

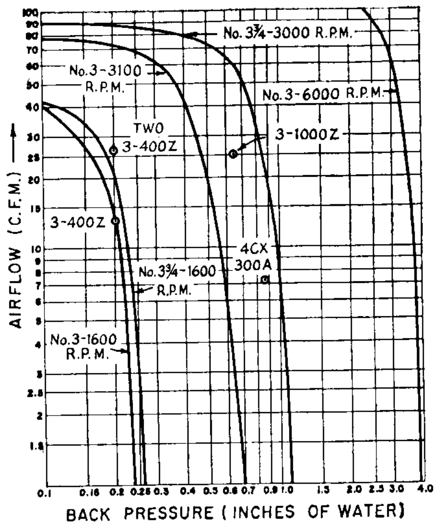

Fig. 6—Typical performance data for 3-, 3½- and 3¾-inch blowers. The low-speed (3100 r.p.m.) No. 3 blower cannot deliver the required flow of air into the back pressure offered by 3-1000Z or 4CX300A cooling systems. The 6000-r.p.m. unit, however, will handle the requirements of any of the tube types indicated, or, in fact, a pair of any of these tubes. Notice that doubling the speed of the blower more than triples the back-pressure capability. Although catalog-rated at "50 c.f.m.," the No. 3¾ 1600-r.p.m. blower is suitable for only low values of back pressure. When the speed is increased to 3000 r.p.m., the same-size blower will handle any of the tubes indicated.

Designing a Forced-Air Cooling System

An application of this design data, as a practical exercise, is the determination of a proper blower to cool a 4CX300A external-anode tetrode in an air-system socket, operating at various values of plate dissipation and 250° C. (maximum) anode temperature. If the ambient (room) air temperature is taken to be 50°C., airflow requirements to hold the tube temperature rise below 200°C at sea level, and at an altitude of 10,000 feet are graphed in Fig. 8. (These curves are based on figures taken from the data sheets for the 4CX300A and 4CX300Y.) If full 300-watt plate dissipation is desired at sea level, the air system must provide 7.2 c.f.m. of air *at the socket* of the tube under a combined tube and socket pressure drop of 0.58 inch of water. At an altitude of 10,000 feet (where the air is thinner), cooling requirements rise to 10.5 c.f.m. at a corresponding back pressure of 0.85 inch.

The additional pressure drops of the cooling system including back pressure developed by the cabinet structure, may be substantial, and must be added to the drop determined for the tube and socket. Unless a manometer is used to check the operation of the complete system, the additional back pressure caused by the duct coupling the blower to the tube and socket is a matter of speculation. If a pressurized chassis is employed having a large, internal open area (plenum chamber) into which the blower works, the additional system back pressure will be obviously less than if the blower has to force air through a flexible hose and around large under-chassis components. Experience has shown that it is generally safe to estimate an additional 50-percent back pressure requirement when the blower works directly into a reasonably clear pressurized chassis area, and this is the most common situation in amateur practice.

Taking the 50-percent extra back pressure requirement as par, an additional back pressure of 0.29 inch of water must be overcome for a total back pressure requirement of 0.58 + 0.29 = 0.87 inch of water for the system. The use of an inexpensive manometer to verify this educated estimate is recommended in the design of new equipment.

Turning to the squirrel-cage-blower data charts, it can be determined that a No. 1 wheel running at 20,000 r.p.m., or a No. 2 wheel running at a speed of 6500 r.p.m. will do the job, as will a No. 2½ wheel operating at 6000 r.p.m.[6] A No. 3 wheel operating at 6000 r.p.m. is more than satisfactory. The No. 3 wheel running at 3100 r.p.m., however, is unsatisfactory, as the graph of Fig. 6 indicates that the impeller "windmills" above approximately 0.6 inch back pressure, and that its output falls rapidly to cutoff zero slightly above this figure. In the interest of minimum noise it would seem prudent to choose a No. 2½ blower running at 6000 r.p.m. to properly cool the 4CX300A with a suitable safety margin. If blower size is a problem, it may be necessary to use a No. 2, higher speed blower at some increase in noise level.

Glass Tubes

Large glass transmitting tubes (above approximately 200 watts plate dissipation) require moderate amounts of cooling air passed over the filament and plate seals to hold the seal temperature below a safe maximum value. As a large quantity of heat is dispelled by infrared radiation from the hot anode, the air requirements of the glass-style tube are usually less than that amount required for an equivalent value of dissipation from an external-anode tube whose anode temperature is limited by the insulator seal. Proper cooling of the glass tube requires that the air pass over the filament seals and then be guided past the glass envelope by a chimney. The chimney must be transparent to infrared radiation from the tube. Lastly, the air passes over the plate seal and is exhausted from the system.

The 3-400Z zero-bias triode, for example, requires 13 c.f.m. at a back pressure of 0.13 inch at the socket, while the 3-1000Z requires 25 c.f.m. at a back pressure of 0.43 inch at the socket. While the amount of air required is of about the same quantity for comparable values of plate dissipation in external-anode tubes, the back pressure demand is considerably less for the glass envelope design, as the air is not required to flow through interstices of a cooling anode.

[6] The curves shown in Fig. 4 and those following, apply to specific models. All models of the same size number and rotational speed (even those of the same manufacturer) do not necessarily have the same performance ratings.

Referring again to the blower and fan charts, it can be seen that a 3-400Z may be adequately cooled by a No. 2 blower (6500 r.p.m.), or a No. 2¾ blower (3100 r.p.m.), when a 50-percent margin is allowed for extra system back pressure. Two 3-400Zs will require twice the c.f.m. at the same back pressure, or a total of 26 c.f.m. at a system pressure of 0.2 inch. In this case, the No. 2¾ blower (3100 r.p.m.) would suffice.

A single 3-1000Z requires 25 c.f.m. at a system back pressure of 0.64 inch (including the 50 percent safety factor), and a single No. 2½ (6000 r.p.m.) blower will do the job.

Either a single 3-400Z, or a pair, may be cooled by a 4-inch axial fan (2800 r.p.m. or higher), as such a device will work into a back pressure of about 0.2 inch. The 3-1000Z, however, cannot be properly cooled by the axial fans listed in Fig. 7.

In all of these examples, full plate dissipation is assumed, and the proper air-system socket and chimney for the tube in question is employed.

The unknown factor in the determination of the overall air-system requirement is the additional back pressure caused by the conduit system or plenum chamber arrangement. This is the reason that the tube manufacturer is reluctant to specify a particular blower for a given tube, as he does not know the characteristics of the overall air system to be used. If the blower works into a reasonably clear under-chassis area sealed for air leaks, and the air is exhausted through the tube socket, the safety factor of about 50 percent in back pressure mentioned earlier should be satisfactory. If, on the other hand, the blower is placed at some distance, with a connecting hose to the socket, blower requirements may rise by a factor of ten or more. *The only safe way to determine the actual requirements of a given air system*

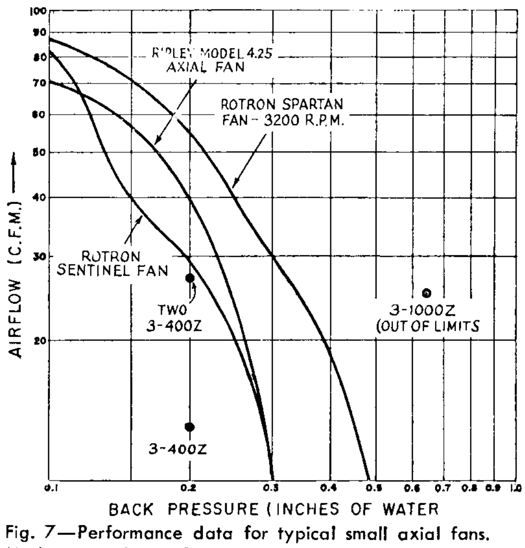

Fig. 7—Performance data for typical small axial fans. Medium-speed axial fans are suitable for a single 3-400Z, or a pair of this type. Axial fans must operate into a plenum chamber that transmits the air to the tube socket without introducing prohibitive additional back pressure. Tube date shown includes 50% extra back pressure, as discussed in the text.

TABLE I

Air requirements and suggested blower data for various air-cooled tubes.
Data is given for single tube, with 50 percent back-pressure allowance.

Tube Type	Socket	Chimney	C.F.M.[5]	Back Pressure (In. Water)[5]	Blower Size	R.P.M.
3-400Z	SK-410	SK-416	13	0.2	3	1600
3-1000Z	SK-510	SK-516	25	0.64	2½	6000
					3¾	3000
4-400A[1]	SK-410	SK-406	13	0.25	3	3100
4-1000A[2]	SK-510	SK-506	25	0.64	2½	6000
					3¾	3000
4CX250B[3]	SK-600 Series	SK-606 Series	6.4	1.12	2½	6000
4CX1000A 4CX1500B[4]	SK-800 Series	SK-806 Series	22	0.3	3	3100
5CX1500A	SK-840 Series	SK-806 Series	47	1.12	3	6000

1 SK-400 socket requires 14 c.f.m. at 0.37 inch.
2 SK-500 socket requires 25 c.f.m. at 0.9 inch.
3 Data applies to 4X150A for 250 w. dissipation.
4 Air requirement for 1000 w. dissipation.
5 Sea level requirements.

is to make back pressure measurements with a manometer.

When in doubt as to the air-system requirements, it is wise to provide an oversupply of air at somewhat greater back-pressure values than estimated by a study of system requirements. It is impossible to damage a tube by too much air, unless the tube is blown out of the socket by the air blast! All low-speed blowers and axial fans should be avoided, too, unless a manometer is used to check out the system under full tube-dissipation conditions.

A summary based upon a 50 percent back-pressure safety factor for various tube and blower combinations is given in Table I.

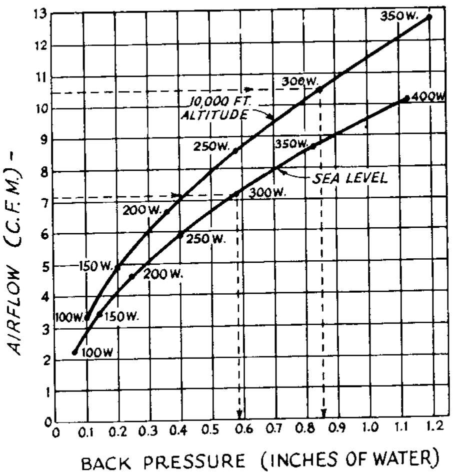

Fig. 8—Typical curves indicating how the cooling requirements increase with an increase in tube plate dissipation. These curves are for a 4CX300A mounted in an air-system socket. The dashed lines point out how the airflow requirements also increase with altitude because of the thinner atmosphere.

Tube Temperature Measurements

Measurement of tube temperature is possible, and the most reliable technique is to use a thermocouple attached to the tube. A somewhat simpler technique for the radio amateur is to determine tube-surface temperature by the use of temperature-sensitive paint.[7] The paint is applied in a *very thin* coat to the tube and dries to a powdery finish after application. At its critical temperature, it melts and virtually disappears. After subsequent cooling, it has a crystalline appearance which indicates that the surface with which it is in contact has exceeded the critical temperature.

Reliable temperature measurements can be made with temperature-sensitive paint only if it is applied in a very thin coat over small areas of the surface to be measured. The substance as supplied by the manufacturer is too thick for use in the presence of forced-air cooling and must be thinned, using only the thinner recommended by the manufacturer. The paint is applied with an air brush or atomizer (or with an aerosol dispenser) in a well-diluted spray, as the amount required to produce a reliable indication is virtually unweighable. A convenient set of equipment for using the temperature-sensitive paints is an atomizer with several vials, each equipped with an airtight cap. One vial may be filled with thinner for cleaning the atomizer, while the re-

7 Temperature sensitive "decals" are also available

(*Continued on page 142*)

mainder are filled with properly-thinned paint sensitive to several different critical temperatures.

Measurements made with temperature-sensitive paint yield basic information sometimes obtainable in no other way, and are the "ounce of prevention" that is worth a "pound of cure."

Conclusion

Tube-surface temperatures are the ultimate criterion by which cooling adequacy may be judged. As tube life is closely related to surface temperatures, reliable temperature or cooling information is very important to the equipment-design engineer and the radio amateur. The proper choice of air blower is important, especially in cases where a high order of back pressure exists in the air system. Use of a manometer to determine back pressure, as well as the use of temperature-sensitive paint, allow the circuit designer to construct a satisfactory forced-air cooling system at the lowest possible cost.

Thanks and appreciation to Bill McAulay, W6KM, Ray Rinaudo, W6KEV, and Bob Sutherland, W6UOV for their suggestions and help in preparing this article. QST