THERMAL DESIGN PART 4

Forced air cooling in high-density systems

The trend toward miniaturization may seem to call for natural convection; but reliability analysis shows forced air cooling can boost system survival by 75%

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☐ Heat sinks alone cannot dissipate excessive heat in a system when the air around them does not move rapidly. The problem is becoming more pervasive as system designers crowd ever larger numbers of circuit boards into ever smaller regions, reducing the number and width of possible air passages. However, air forced through the narrow passages by a fan will remove the heat and thereby raise the life expectancy of a high-density electronic system.

Two other factors that contribute to a system's tendency to overheat and so detract from its long-term reliability are: the increasing density of the circuitry on the chips inside the IC packages, and the increasing speeds at which this circuitry operates. These trends, too, are helping to spread the use of forced air cooling, which is also highly effective in smoothing temperature fluctuations at critical semiconductor junctions in densely packed, high-speed logic systems.

In the past, however, the pressure to optimize reliability has made packaging engineers hesitant to add an electromechanical fan to an electronic system that contains no moving parts. But the reliability of air-moving devices has recently risen an order of magnitude, improvements having been made in the insulating materials in stator windings and in the application of precision bearing design. The mean time between failures of a fan moving air at 100 cubic feet a minute at 158°F can by now reach over 50,000 hours.

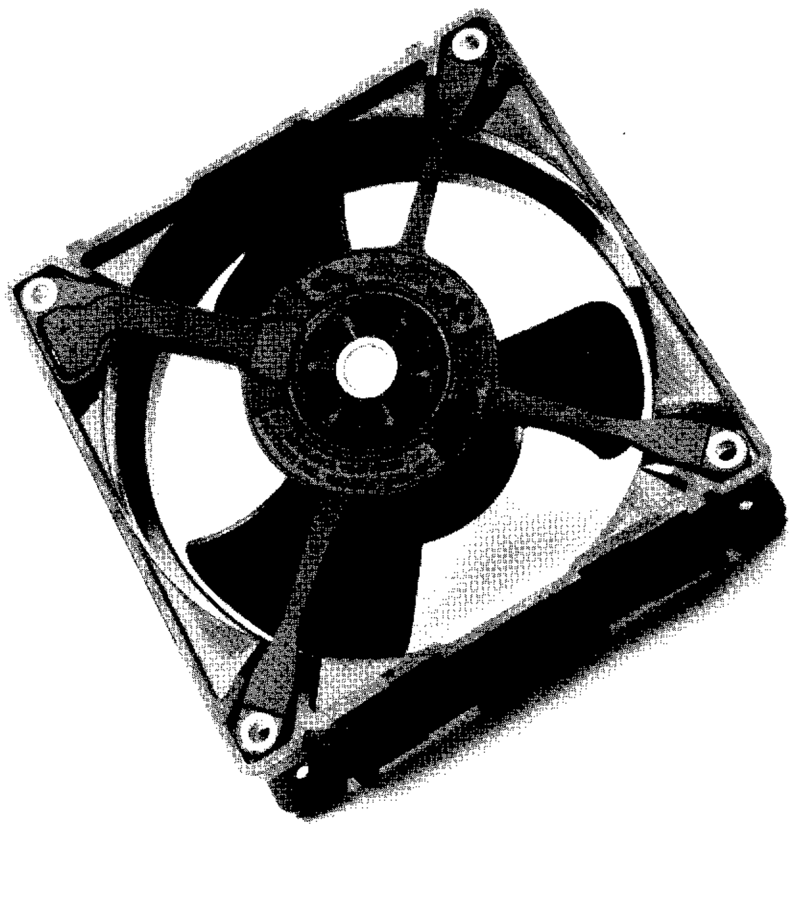
The limitations of natural convection

Buoyancy is the driving force moving air in a natural convective air stream. But buoyancy can't deliver velocity much over 0.5 foot per second. The reason is that the specific weight of warmed air doesn't differ appreciably from that of the cooler air surrounding it. And when this small buoyant force must also overcome the counteracting viscous phenomena that develop along stationary air masses, the air flow rate is limited to a fraction of a foot per second. This is serious because the thermal path between a stationary wall and an air stream moving at velocities below 0.5 ft per second is relatively poor.

Figure 1 illustrates how the velocities and the thermal profiles of air moving past a stationary wall affect heat transfer. The velocity plot indicates that the speed of air at the boundary is zero because at the boundary air particles adhere to the wall. As the distance from the wall along the y axis increases, the velocity of the air also increases until it reaches the mainstream velocity. As for the temperature profile, notice that the air temperature at the wall is virtually the same as the wall temperature, and diminishes along the y axis to the value of the mainstream air temperature.

The shape of the velocity profile is crucial because the coefficient of heat transfer at the wall is a function of the rate of change of the temperature along an axis perpendicular to the wall. Increasing the flow rate enlarges this differential and thus the effective heat transfer from

Life saver. Typical modern fan can add 75% to the expectation of system survival. Device delivers 70 ft^3/min when driving a static load that's the equivalent to 0.1 inch of water.



the wall to the air stream. Since the natural-convection flow rate is limited, the value of this differential is also limited. However, forced air can develop velocities far in excess of those attainable with natural convection, enhancing the transfer of heat across the boundary.

Faster air flow yields a second benefit because speed increases the temperature differential between the moving air stream and the stationary wall being cooled. This is important because heat transfer is also a function of temperature differential. The larger temperature differential results because a molecule of air at higher speeds has little time to absorb heat, so it will not reach as high a temperature as a slower-moving air particle.

Thus faster air flow increases both the coefficient of conduction and temperature differential.

The goal behind improving heat transfer in a system is of course greater reliability. Proof that adding an air-moving device to a system that formerly relied on natural convection does extend a system's life is given by the following case history.

Bathtub curves

The curve labeled (a) in Fig. 2 is the survival expectation of a minicomputer packaged in a 36-by-12-by-12 in. envelope which employed natural convection cooling. The "early and chance failures" portion of the curve—the infant mortality region—describes the time interval immediately following manufacture, when marginal and defective components are weeded out. The second portion of the curve—"random and chance failures"—describes the useful life of the system. The final portion of the curve, "wearout and chance failures," signifies the wearout period of the equipment's life span where the failure rate climbs rapidly.

Originally the manufacturer had relied upon the natural convection of air to cool the ICs and other components and maintain temperatures below safe values. But the high packaging density of the equipment prevented the air flow from cooling all heat sources adequately, and average life expectation, as indicated in Fig. 2, was about 20,000 hours. This life span was too short, so the manufacturer turned to forced air cooling.

The forced-convection heat-transfer equation is:

$$Q = C_p W \Delta T$$

where Q = amount of heat dissipated, C_p = specific heat of air, W = air mass flow rate, and ΔT = temperature rise through the system. Incorporating conversion factors and specific heat for air at sea level yields an equation for the flow rate required to dissipate a given amount of power:

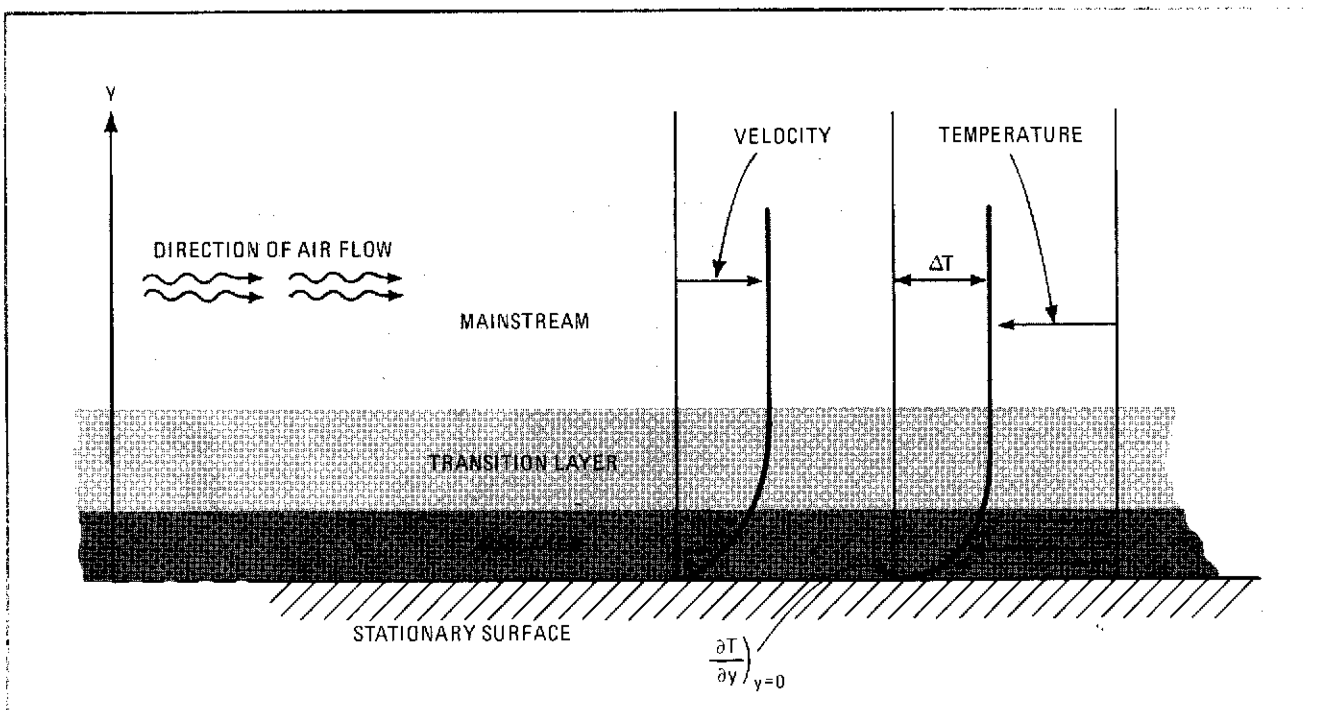
$$CFM = (3160 \times kW)/\Delta T°F$$

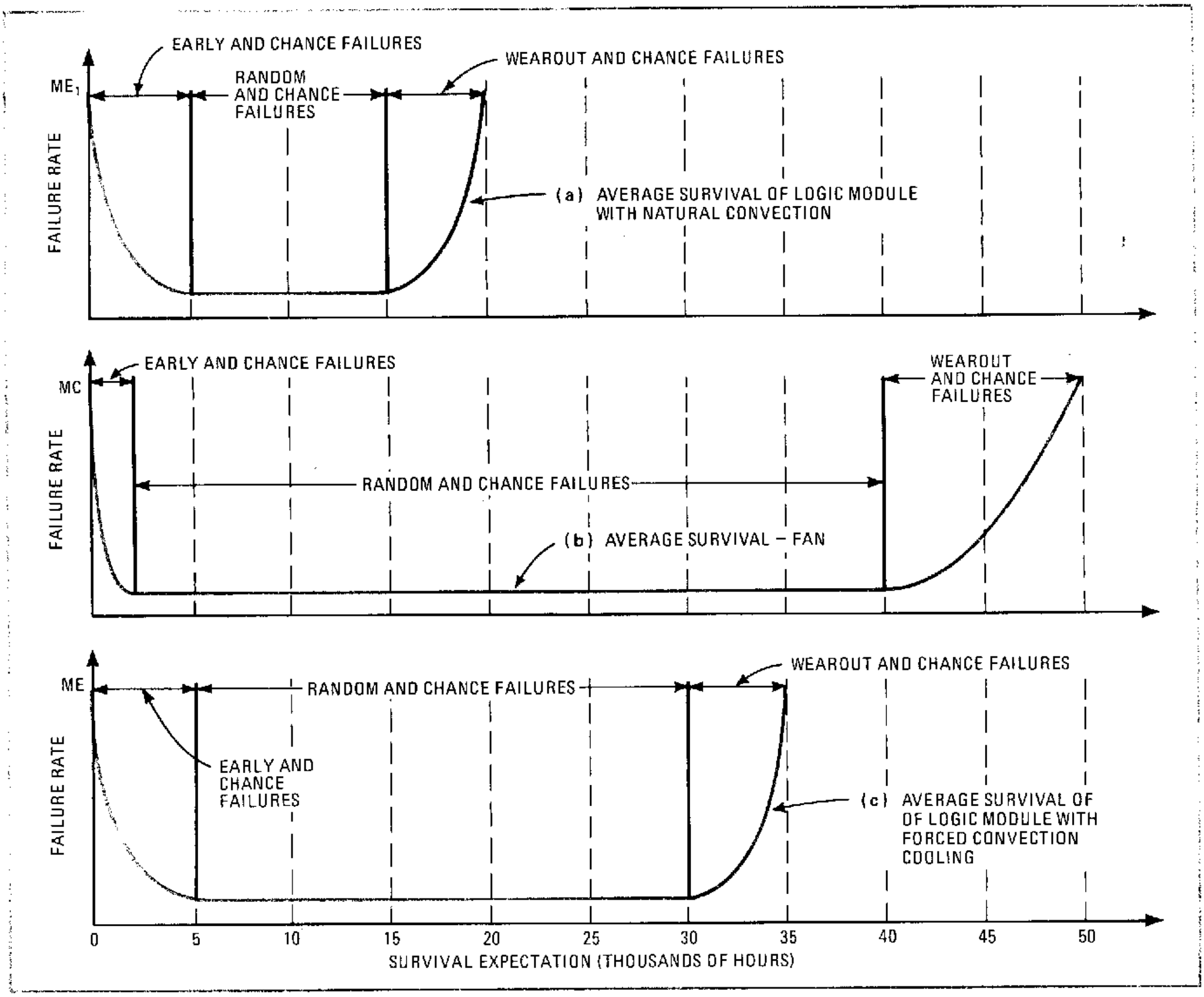
where CFM = flow rate measured in cubic feet per minute at an air density of 0.075 lb/ft^3; kW = power dissipated within the system enclosure, in kilowatts; and ΔT = average temperature rise of air passing through the system, in degrees fahrenheit.

For the minicomputer, the maximum allowable temperature within the cabinet and the maximum ambient were determined to be 113°F and 68°F, respectively. Secondly, the total power dissipated within the cabinet was computed as 1 kilowatt. These numbers, when substituted in the above equation, work out at $(3160 \times 1\ kW)/(113 - 68)°F$, or 70.2 ft^3/min.

The system was then subjected to an aerodynamic

1. Convective interface. Plots depict the velocity profile and the temperature profile of the boundary between a cooling air flow and a stationary surface. Optimized convective cooling requires the rate of change of temperature at the boundary and the temperature differential between the wall and the mainstream to be maximized along an axis perpendicular to the wall.





2. Stretchout. Survival expectation of a minicomputer (20,000 hours) was extended to some 35,000 hours by adding a fan. Such life extension runs counter to the common belief that a forced-air-moving device degrades reliability.

study to determine its resistance to air flow. This turned out to be 0.1 in. water-gauge static pressure at 70 ft^3/min.

On the basis of this data the fan shown on page 87 was selected. It measures 4-11/16 in. square by 1½ in. deep. Packaging engineers were able to accommodate it in the original equipment enclosure by rerouting some wire harnesses and moving several fasteners. The cost was less than one cent per watt dissipated. The fan occupied less than 0.5% of the enclosure volume.

Life tests of the fan indicate an average survival of 50,000 hours at 158°F, plotted as curve (b) in Fig. 2. The "early and chance failures" as plotted are really quite conservative. The reason is that electrical failures, which used to account for many of the early failures in air-moving devices, have been drastically reduced as a result of improved magnet-wire insulation and rigorous inspection procedures. Bearing failure is the principal wearout failure mode.

Increased survival

Addition of the fan raised the minicomputer's survival expectation from 20,000 to 35,000 hours—an improvement of 75%. This survival expectation is plotted as curve (c) in Fig. 2.

This curve is based on the formula:

$$ME = MC - [ME_1 + (MC - ME_1)]K \text{ hours}$$

where ME_1 is the average survival for the over-all system with natural convection cooling, MC is the average survival rate for air-moving device, and K is an empirically derived derating factor. Therefore, when ME_1 = 20,000 hr, MC = 50,000 hr, and K = 0.3, ME works out at 35,000 hr.

The result is conservative because the derating factor, K, generally used by system and air-moving equipment manufacturers, is in the neighborhood of 0.12 rather than 0.3 as shown. Thus survival values determined by the formula given with a derating value of 0.3 can be interpreted to mean "at least as good as."

The formula can be applied generally to ascertain the increase in survival attainable by adding an air-moving device. Should empirical data for the over-all system be lacking, the designer can combine the survival rates for individual components by employing traditional reliability analysis techniques. □