THERMAL DESIGN PART 7

Air through hollow cards cools high-power LSI

Providing parallel flow through hollow-core cards and wafer-mounted heat exchanger can cut temperatures at no cost in space

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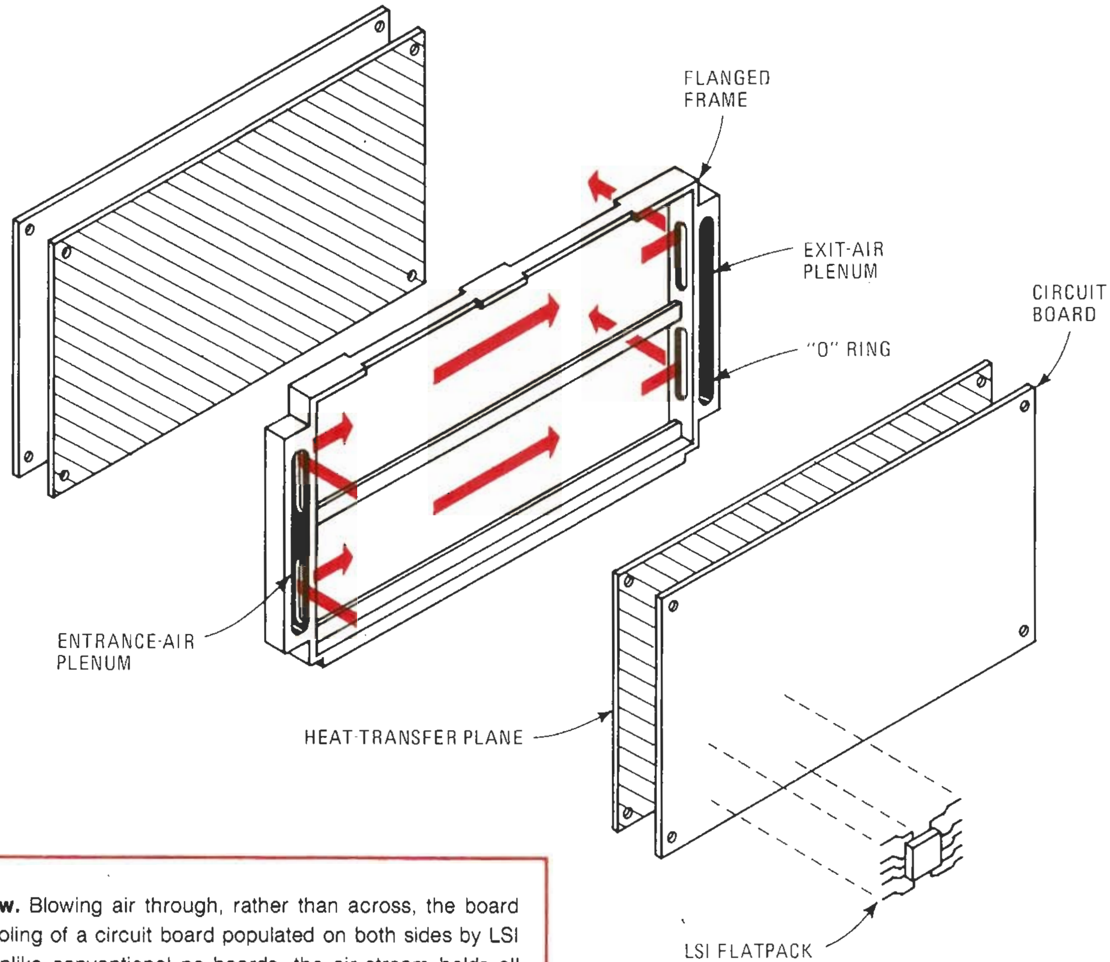
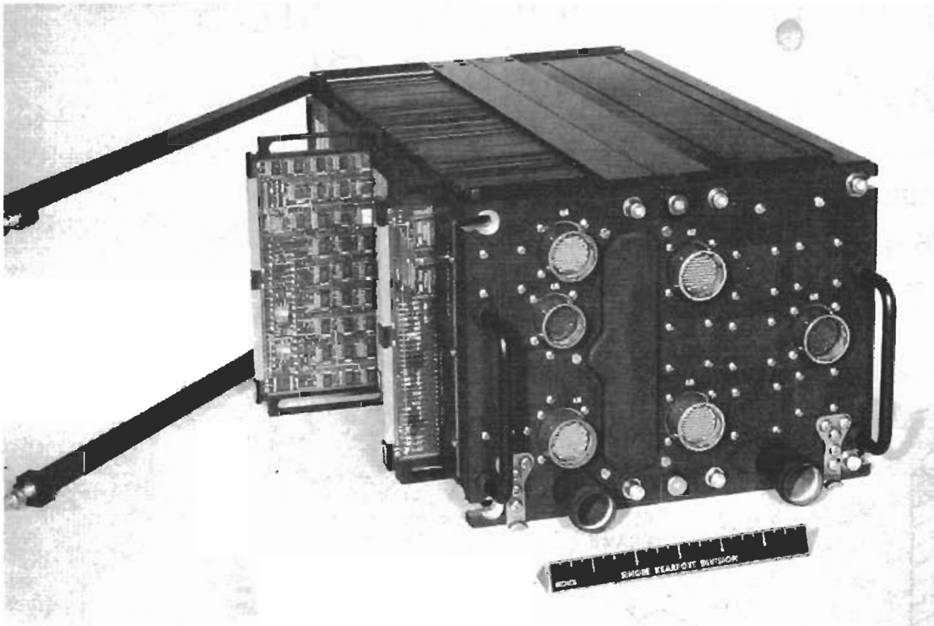


1. It's hollow. Blowing air through, rather than across, the board optimizes cooling of a circuit board populated on both sides by LSI packages. Unlike conventional pc boards, the air stream holds all components near the same temperature.

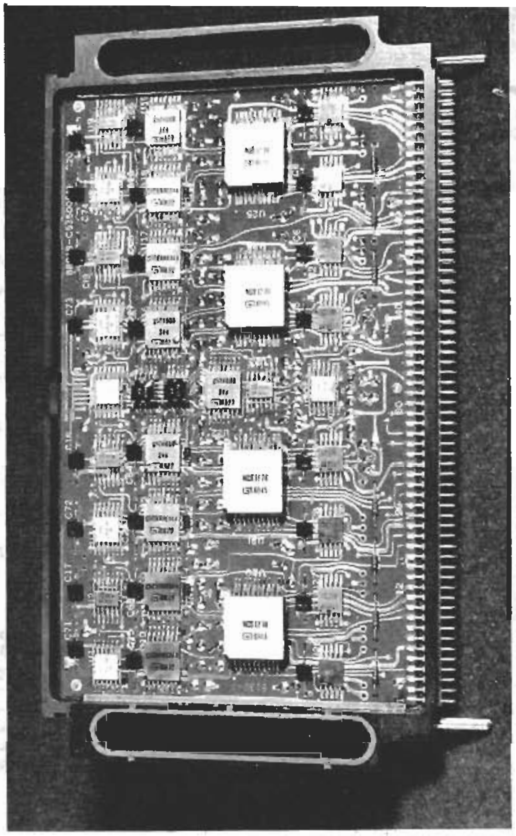
☐ Circuit designers are excited about the tremendous functional capability of LSI, and they are constantly trying to increase the number they can pack on each printed-circuit board. However, dense packing of thousands of active, heat-producing devices on a square inch of circuit card places an awesome burden on the packaging engineer.

Traditional cooling methods are becoming increasingly inadequate, especially with densely packed high-power LSI devices, because power density, in watts per cubic inch, is much higher, and thermal paths from the heat-producing devices to the cooling medium are too long. It's not unusual for a logic card of 25 square inches, which once dissipated 2.5 watts, to dissipate 20 W when mounting LSI and MSI devices.

However, thermal paths can be shortened and temperatures of device junctions held well below safe values by using a patented hollow card so that the heat exchanger becomes an integral part of the circuit card. Air circulates through a channel between the two circuit



2. Potent package. Airborne computer packs 35 hollow cards containing over 2,500 flatpacks. Total power dissipated is over 400 watts, but device temperatures never climb above 75°C, thereby enhancing long-term reliability. Slots shown in the top and bottom of the cards form the entry and exit air plenums.



3. Anatomy. Packing over 60 LSI flatpacks, this card dissipates over 20 watts, almost 10 times more than its conventional printed-circuit-card ancestor. Cool air enters at left and exits from the plenum at right.

cards mounted back-to-back, and results are truly astounding. What's more, the hollow configuration weighs no more than a conventional card cooled in a conventional way.

Better still, thermally, is the basic building-block module (B^3M), which Singer-Kearfott has designed for the U.S. Naval Air Systems Command. The module, which has eliminated the circuit card altogether, lowers the temperature of the IC junction from 141°C to a safe 68°C, while the ruggedized package is easily accessible and easy to interconnect.

Design objectives

Clearly, two factors discourage the conventional design approach: component temperatures are highly dependent upon card location in the chassis, and the temperature rise across the horizontal span of each card is too great because ICs near the center of the card build up intolerable temperatures. (See "LSI turns up the heat," p. 115).

True, a designer could use heat pipes, but they are expensive. A better and cheaper solution is to introduce cooling air at a common temperature to each card and then circulate the air directly through each card. This can be done most effectively by circulating air through a hollow-core card.

The configuration of the hollow-core card provides improved cooling by:

- Eliminating the thermal conducting path across the breadth of the circuit card.
- Replacing series air distribution with parallel air distribution.
- Increasing convection area per circuit card.
- Increasing convection effectiveness.

A design for a hollow-core card that satisfies design objectives for a high-power, high-density system is illustrated in Fig. 1. The assembly is actually a sandwich of two cards, mounted back-to-back on a flanged frame, which separates the cards to create a channel that allows cool air to flow across their rear surfaces. Bonded to the back of each card is a conductive heat-transfer plane, which serves as the convective interface.

The air enters a plenum on the left side of the frame and exits at the right. The reason that cooling air entering the inlet plenums of cards positioned at increasing distances from the air source does not get hotter is that the temperature gradient along the main air-cooling stream, perpendicular to the cards (the left side of Fig. 1), is virtually zero. The transverse flow rate at the entrance to each card is determined by careful selection of the cross-sectional area of the entrance and exit air plenums.

The hollow cards are clamped together by straps between their front and rear panels. The upper pair appears in Fig. 2. The lower straps (not shown) serve as a subchassis that supports the motherboard and the mating connectors for each card.

A close-up of a hollow-card assembly that mounts LSI flatpacks is shown in Fig. 3. Note that gaskets line the edges of the cooling-air entry and exit plenums to prevent air leakage. Besides assuring a uniform temperature at each card-inlet plenum, parallel cooling maintains a virtually constant air-pressure drop, regardless of the number of cards. In the traditional chassis-type heat exchanger, the card interface temperatures increase as cards are added so that the cooling effectiveness falls off

LSI turns up the heat

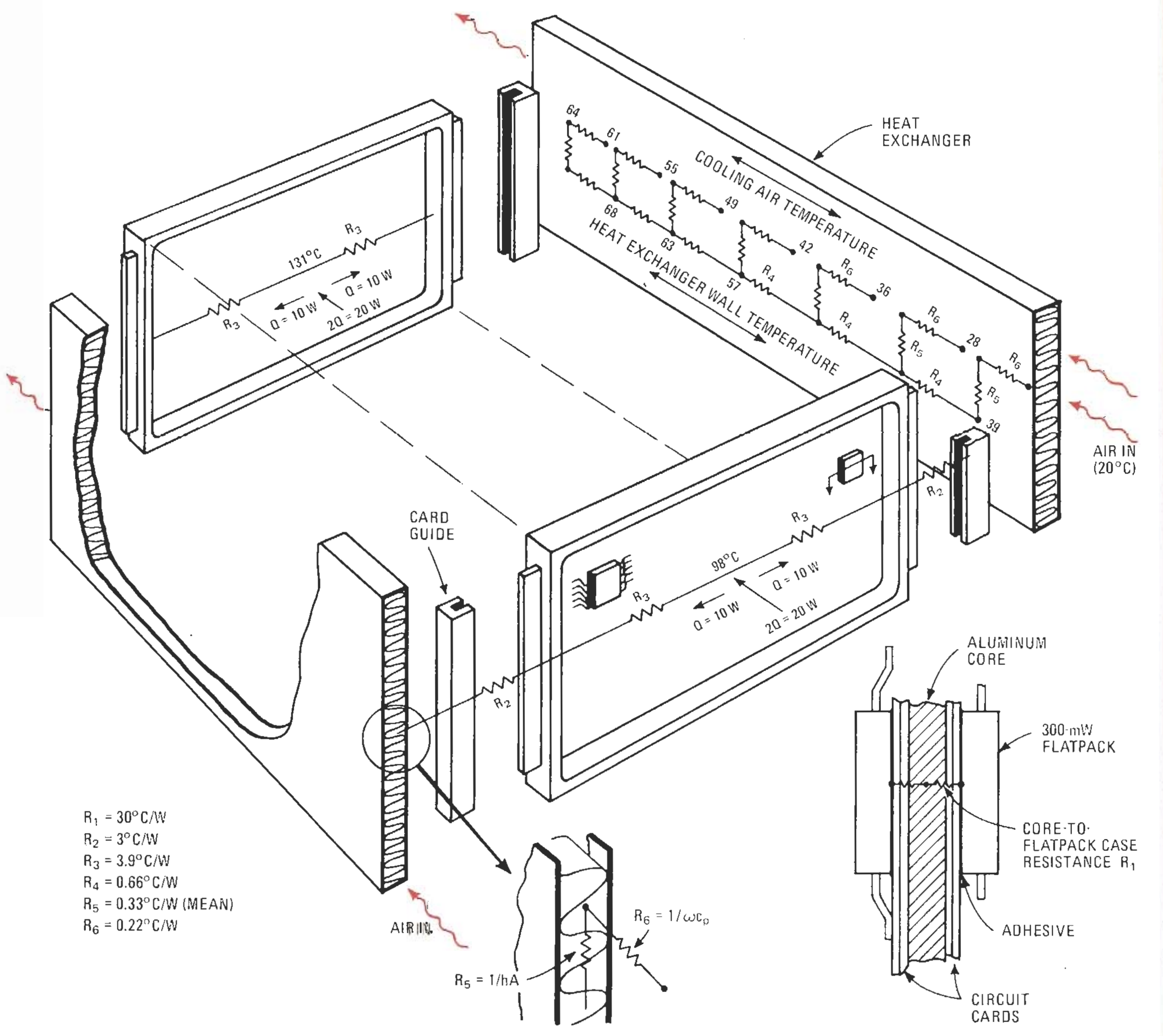
When it was populated by discrete components, the card shown below cooled the circuits on it admirably. But when large-scale integration multiplied the power density to as much as 500 milliwatts per square inch, this configuration could no longer fill the bill. Originally designed for an airborne computer, the chassis contained 35 cards that dissipated a total of 85 watts. A power supply raised the burden of thermal dissipation by another 65 W.

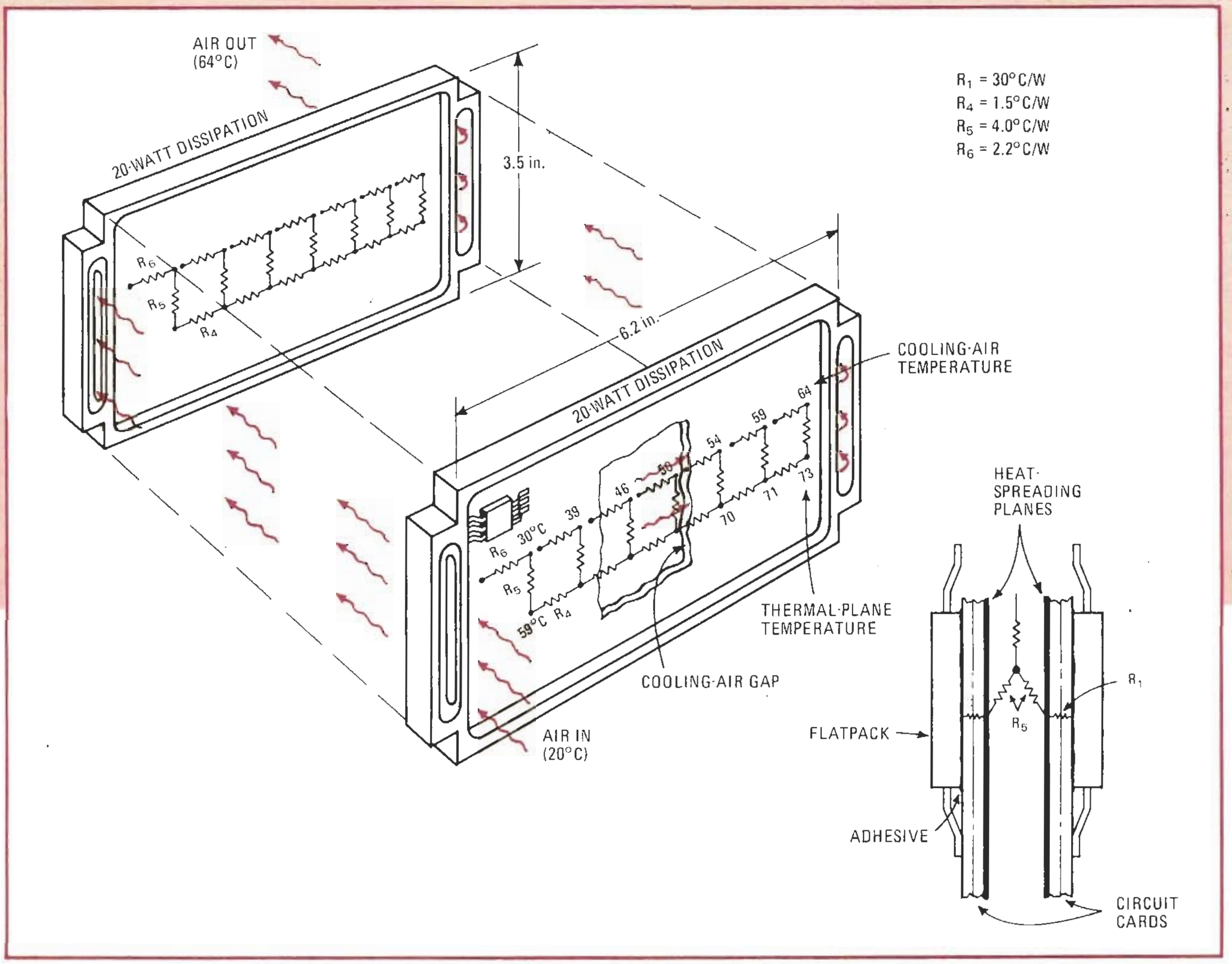
Circuit cards, some built on aluminum cores, conduct heat left and right to the air-cooled heat exchangers, which double as chassis walls. The card guides also serve a vital secondary role—carrying heat from the card to the exchangers. When each card dissipated 2.5 W, the cooling air could keep temperatures below a safe 75°C. However, when each card is packed with 60 LSI flatpacks, each measuring 0.25-inch square, the power on each card is boosted to 20 W, which drastically increases the amount of heat that must be dissipated.

If cooling air at 20°C is forced through the exchangers at three pounds per kilowatt, the temperatures at various points in the chassis will reach the temperatures assigned to the node points in the illustration. There is a colossal rise of 49°C laterally across the card. Although the edge temperature is only 39°C, the center of the near card is 98°C. The temperature of the last card at the rear, near the outgoing air, rises to 131°C—well above the tolerable levels for long-term IC reliability.

A designer could improve heat flow in the existing design by increasing the card-core thickness and by using a wedge-type card clamp, which would improve thermal conductivity. But this effort won't lower IC temperatures very much. Even a tripling of the card-core thickness fails to lower maximum IC temperatures below 92°C— too high for long-term reliable operation. Moreover, thickening the card is a costly tradeoff because it doubles the card weight and enlarges its volume by 30%.

Fortunately, the hollow-core card and the basic module with its integral exchanger are breakthroughs in thermal architecture. They both enable cooling air to circulate effectively and thereby provide the parallel air to hold densely packaged LSI devices at low operating temperatures.





4. Flow path. Entrance air at 20° C distributes to each of the cards and exits at 64° C. Air temperature at entrance plenums of all cards is virtually the same. Circuits depict thermal paths. Resistor R_5 accounts for the thermal resistance of the convective interface.

as the distance from the air intake increases.

The hollow card successfully lowers component temperatures below what is obtainable in conventional designs. Using a design rule of three pounds per minute of cooling air per kilowatt, a card dissipating 20 W is allocated 0.06 lb of cooling air. As shown in Fig. 4, the air's exit temperature is 64°C if the inlet temperature is 20°C. The circuit card's thermal-plane temperature range is from 30°C to 64°C, and maximum and average component-case temperatures are 82°C and 74°C, respectively.

Table 1 compares case temperatures and indicates that the hollow card provides significantly lower component temperatures because the hollow region assures that cooling air is brought within close proximity of the heat-dissipating devices.

Convection efficiency increased

As an additional benefit, the geometry of air-core cards boosts convection efficiency. The convection coefficient, which is a function of air speed, rises because the shortened cooling path speeds air flow through the hollow card and also prevents buildup of a static boundary layer, which hinders heat transfer. The path in the air-core card is 6 inches long, compared to 15 in. for the conventional card.

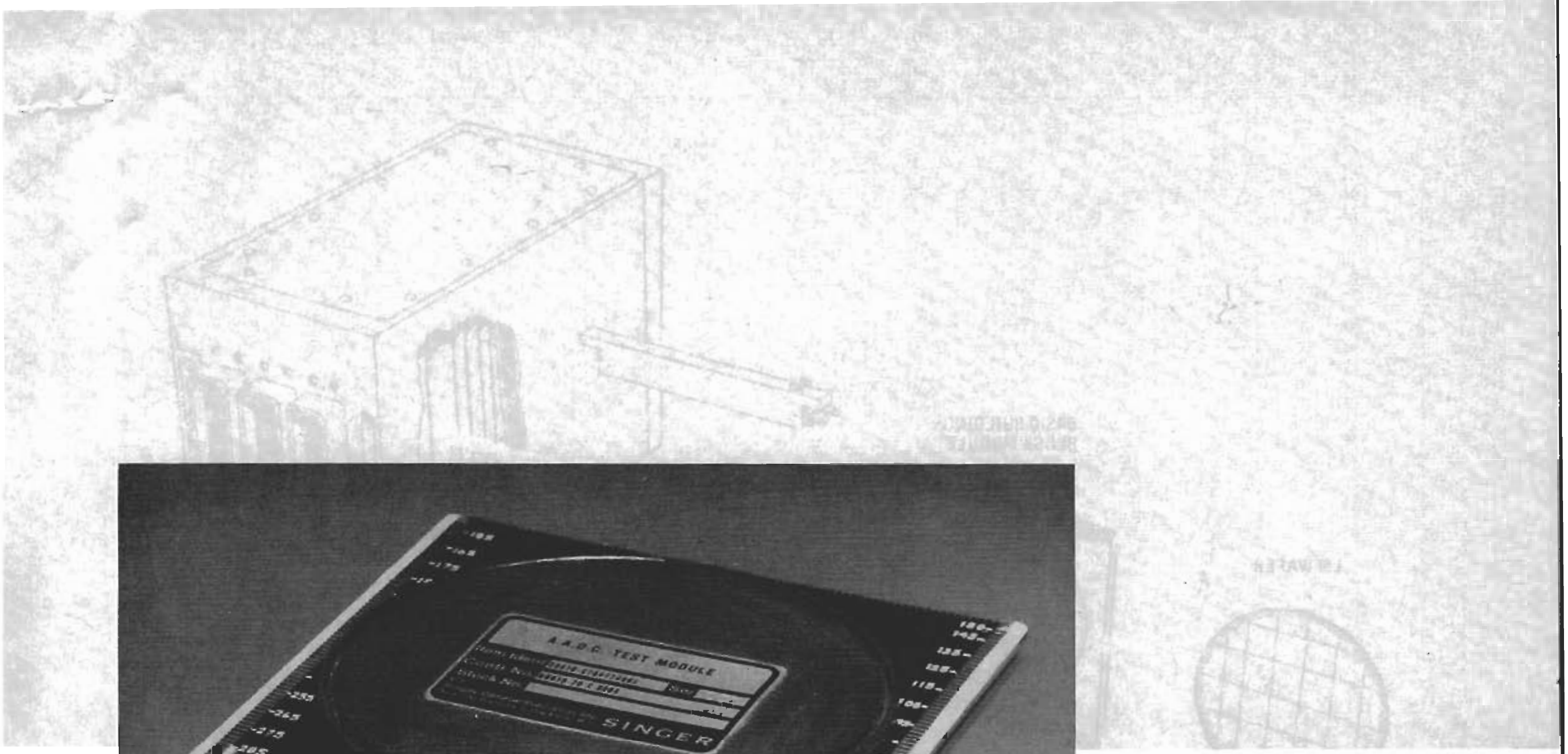
Finally, the surface area of the hollow card presents 20% more convective area to the moving air stream than does conventional designs. If cooling is still inadequate, a designer can furthur enlarge the convective area by adding fins along the surface. A finned exchanger becomes practical when the power dissipation per card exceeds 25 W, not unusual in power supplies.

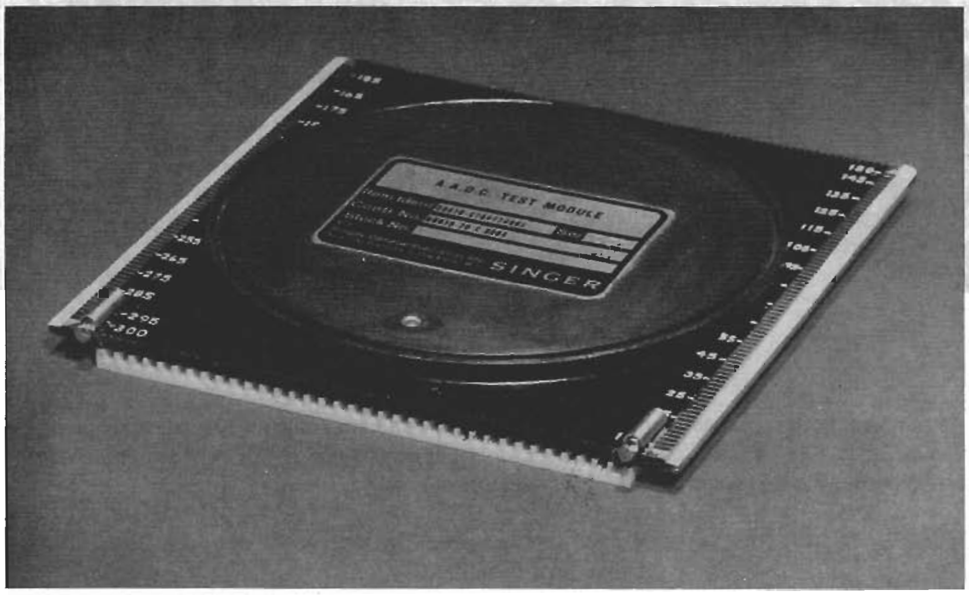
A system approach

Efficient as the hollow card is, one more improvement can be made. That's to reduce the resistance of the path from the chip to the thermal plane of the card.

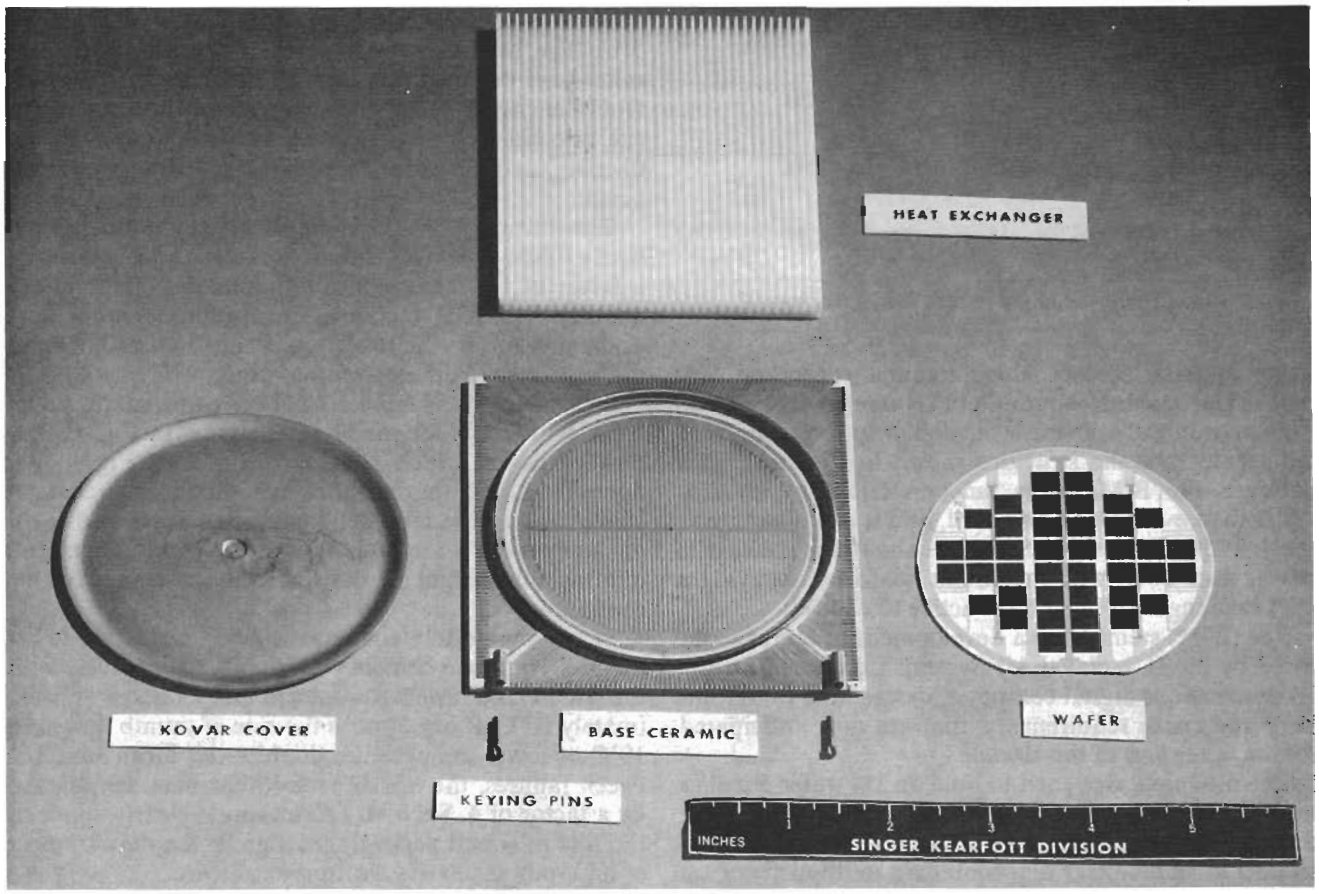
In the LSI flatpack, junction-to-case thermal resistance ranges from 20°C/W to 75°C/W so that if a package dissipates 300 milliwatts, the junction temperature rises 6°C to 22°C above the case temperature. Junction-to-case thermal resistance is a major contributor to temperature rise, and if not lowered, can be a significant factor in loss of reliability.

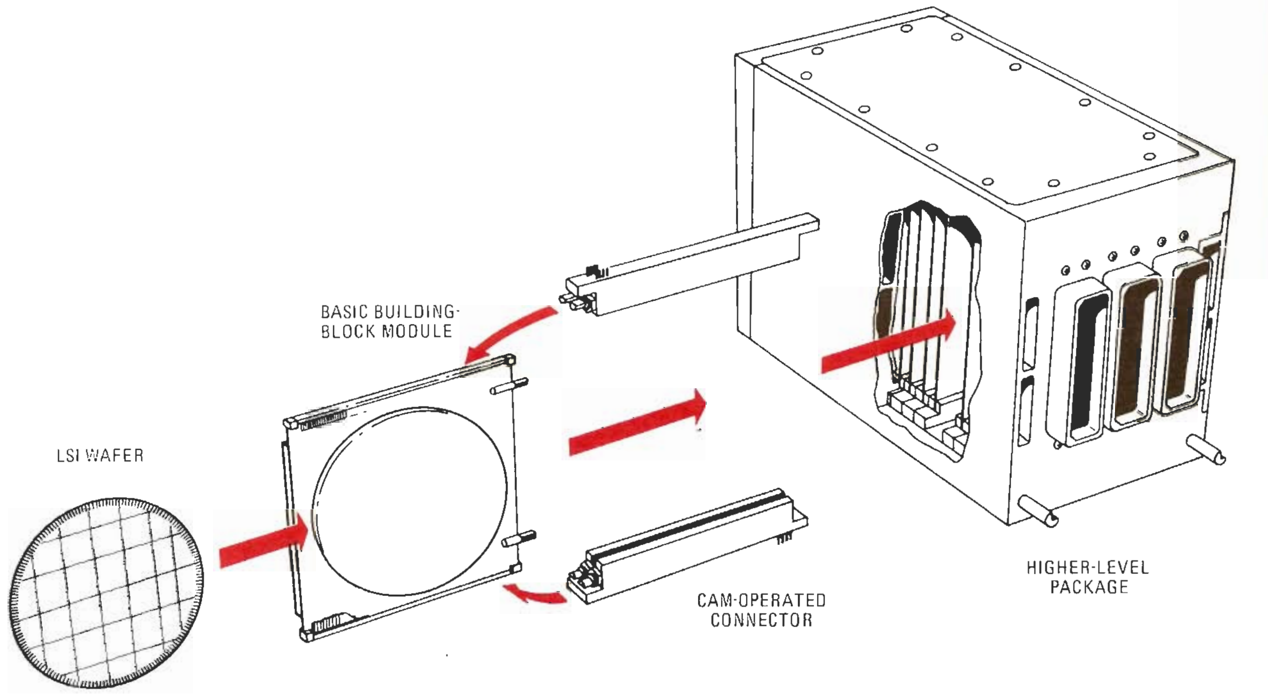
Improving the thermal path within the flatpack is difficult because effective heat transfer depends heavily on a lateral spreading effect as the heat moves from the device junction toward the interface between the package and the circuit board. Attempts to improve heat flow by selecting a better thermal conductor or a thinner sub-





5. A cool wafer. Efficient thermal package houses a 3-inch LSI wafer (a). Component parts (b) include an alumina or beryllia heat exchanger that fastens directly to the base ceramic, optimizing cooling. Substituting more costly beryllia enhances thermal conductivity by a factor of 12.





6. Full-wafer packaging. This airborne computer houses modules containing 3-inch wafers, doing away with the printed-circuit-card construction and holding device junctions below 68° C. Cam-operated connectors eliminate engagement force. At 400 W, higher-level package dissipates almost three times the power of an earlier computer—with no increase in package volume.

COMPONENT-CASE TEMPERATURES – 20-WATT CARD		
	Hollow card (°C)	Conventional card (0.05-in. aluminum core) (°C)
Maximum IC case temperature	82	131
Average IC case temperature	73	115
Cooling-air temperature rise	44	44
Flow rate 3 lb/minute per kW – 20°C inlet air temperature		

strate material seldom lower thermal resistance very much. The problem requires a novel solution.

Extraordinarily potent in its ability to lower junction temperatures is the structure shown in Fig. 5(a). This package, the B³M, offers junction temperatures 23% lower than even the hollow card, and it can dissipate as much as 50 W. What is so unusual about this package is that it does away with the circuit board by marrying a heat exchanger directly to the active IC devices.

The (B³M) stems from a development program sponsored by the U.S. Naval Air Systems Command for the all-applications digital computer, designed to fulfill military and space requirements that are now anticipated for the latter part of this decade.

The module is designed to hold an LSI wafer 3 inches in diameter that has a complexity equivalent to more than 5,000 gates. Alternately, it can house a hybrid substrate 3 in. in diameter that contains a multiplicity of LSI chips and passive devices mounted on a multilayer thick-film substrate.

The key to the excellent thermal capability of this module is the ceramic heat exchanger shown in Fig. 5(b). The heat exchanger cements directly to the alumina-base ceramic, ensuring a very short thermal path from the chip to the cooling air stream. Interrupted fins can also be used to prevent static air boundaries from forming, and the reward is a high film-convection coefficient.

Substituting more-costly beryllia for alumina in the heat exchanger lowers thermal resistance still more—by a factor of 12—thereby lowering junction temperatures another 8°C. The combination alumina-beryllia heat exchanger lowers the lateral resistance so that hot spots are less likely to develop on the chip.

Singer-Kearfott's higher-level package, made up of basic building-block modules, is shown in Fig. 6. Airflow paths are much like those shown in Fig. 1. Air flows from left to right through the heat exchanger channels on each module. Again, flow rates and inlet-air temperature are independent of card placement, offering the designer great flexibility in arranging the configuration.

The basic module circulates cooling air where it belongs—in intimate contact with the IC. Doing away with the circuit card lowers IC-junction temperatures approximately 20°C. If one applies the rule of thumb that each 10°C of lower temperature doubles the mean time between failures, the life of each IC has been lengthened by a factor of 4. Such an enhancement clearly supports the role of sound packaging design in the development of high-power-density electronic systems. □