Thermoelectric heat pumps cool packages electronically

Decreased costs and improved reliability of these solid-state modules warrant a new look at a versatile thermal management technology

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☐ As the packing density of integrated-circuit–chip packages continues to soar, the heat dissipation in equipment grows proportionally, making heat management of electronic systems vital to the design engineer. The improved and cost-efficient thermoelectric heat pump—a fully electronic module that can heat or cool a component or group of components—represents a versatile and available thermal management tool that engineers cannot afford to overlook.

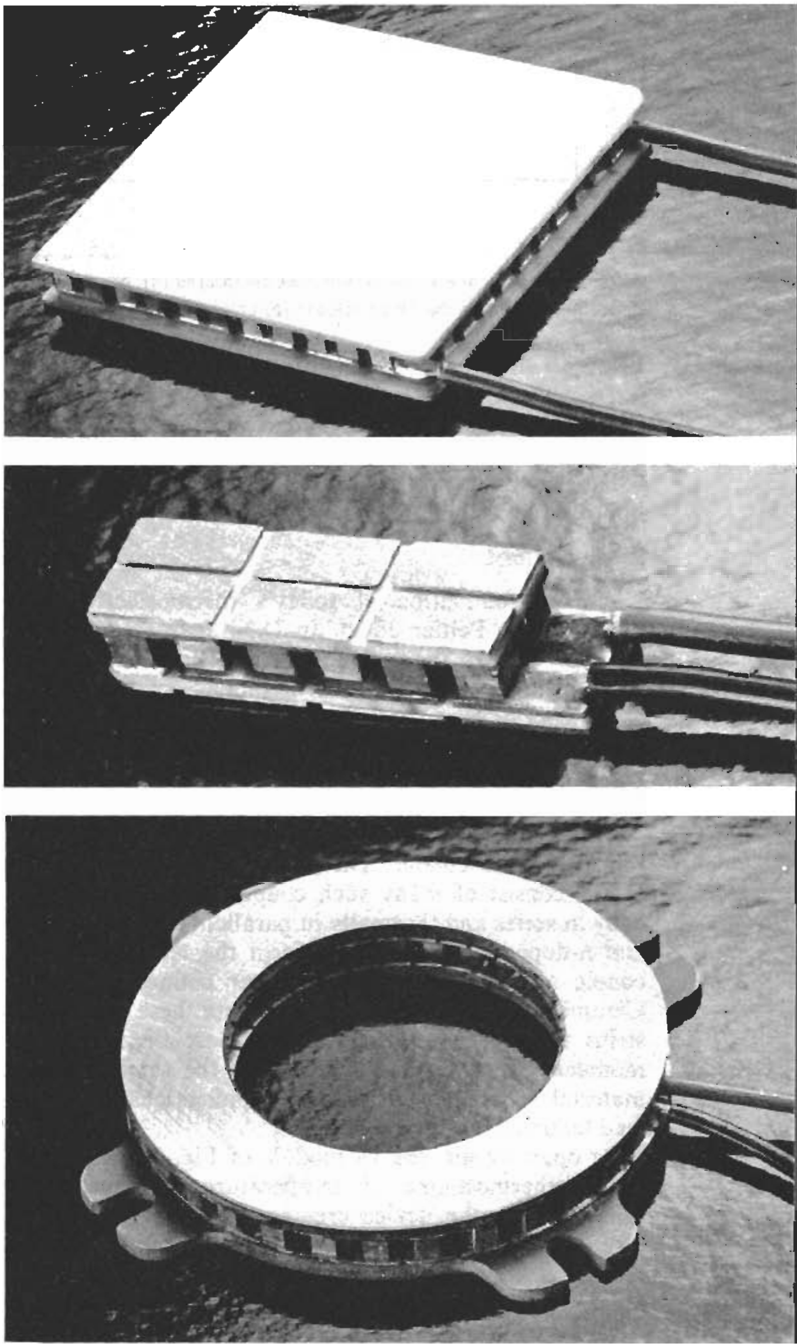
Thermoelectric heat pumps are solid-state devices with no moving parts. With a suitable electrical power input, they pump heat from one side of the device to the other. Available in a variety of shapes and sizes, they provide one of the few means to cool objects to well below ambient temperatures. In addition to cooling, thermoelectric (TE) devices can generate heat and electric power. Some typical devices, or modules, are illustrated in Fig. 1.

Renewing interest

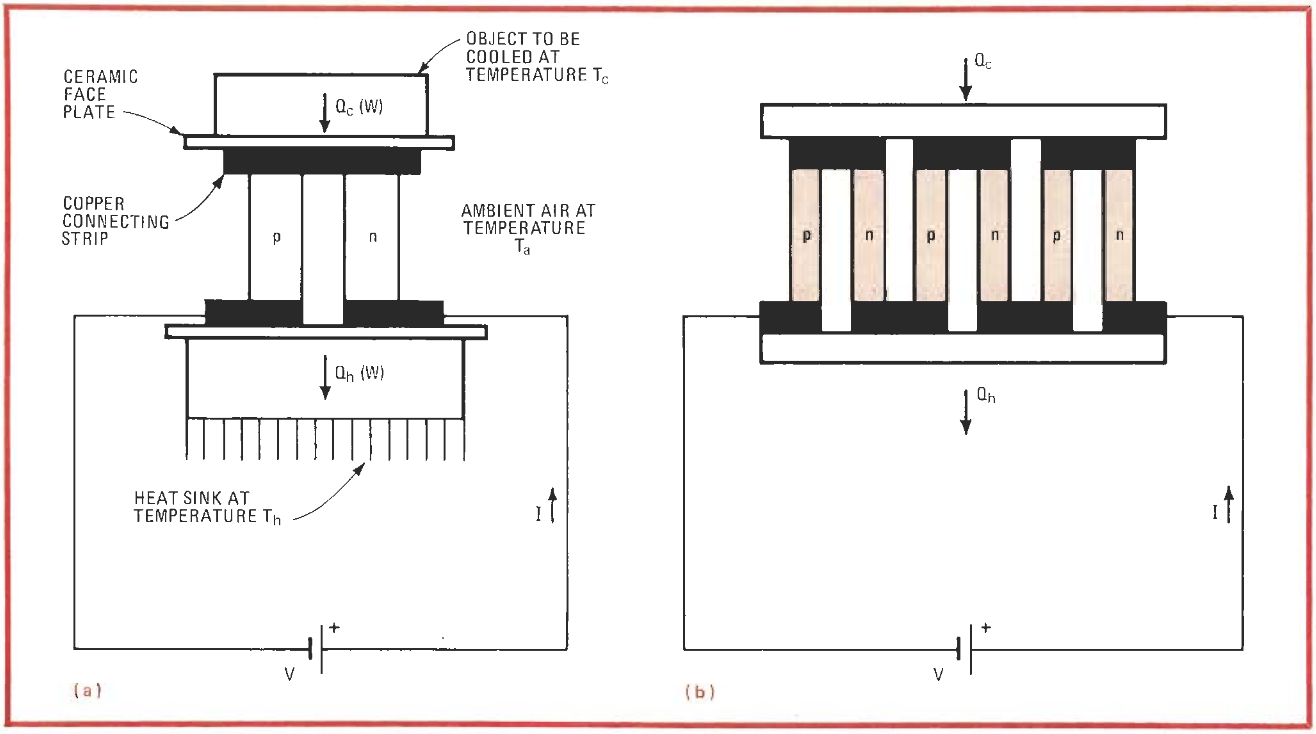
TE devices were originally developed during the 1960s to meet exacting, bulky, and expensive military and aerospace temperature-control applications. When they failed to compete economically with conventional electromechanical cooling techniques for mass applications (such as home refrigerators), most large companies, and industry in general, lost interest. Since then, they have found use primarily in special-purpose applications, such as cooling infrared detectors and maintaining sample temperatures in blood analyzers.

Throughout the 1970s, thermoelectric devices suffered from a distinct lack of promotional effort. Most recent graduates know little about them, though more experienced engineers remember the difficulties that plagued them during the 1960s. Recently, however, the following important developments have shown that thermoelectric cooling deserves closer examination by today's design engineers:

■ TE device cost has fallen dramatically. A typical cooling module that sells for from $20 to $30 today sold for over $100 in 1975. (These figures are for quantities



1. Electronic heat pumps. These thermoelectric modules are solid-state electronic heat pumps. With a suitable electrical power input, they actively pump heat from one side of the device to the other and can cool objects to well below ambient temperatures.



2. TE operation. In a single thermoelectric couple (a), application of suitable electric current causes heat to be pumped from cold object to heat sink. Several of the TE couples in (a) can be connected electrically in series and thermally in parallel (b) to increase capacity.

below 10 and have not been adjusted for inflation.)

- TE devices are now available in a wider variety of shapes and sizes for a much wider variety of applications than before.
- Device quality, reliability, and delivery time have all improved greatly.

Peltier effect

At the foundation of today's thermoelectric heat pumps is the Peltier effect. In 1834 Jean C. A. Peltier discovered that the passage of an electrical current through the junction of two dissimilar conductors can either cool or heat the junction depending on the direction of the current. Heat generation or absorption rates are proportional to the magnitude of the current and dependent on the temperature of the junction.

Figure 2a shows a simplified schematic of a single thermoelectric couple. The thermoelectric modules of Fig. 1 consist of many such couples connected electrically in series and thermally in parallel (Fig. 2b). The p- and n-doped semiconductors form the elements of the couple and are soldered to copper connecting strips. Ceramic faceplates electrically insulate these connecting strips from external surfaces. In most thermoelectric modules, doped bismuth telluride is the semiconductor material. For high-temperature applications, however, lead telluride is often used.

At open circuit, the TE module of Fig. 2a acts like a simple thermocouple. A temperature gradient maintained across the device creates a potential across its terminals proportional to the temperature difference, ΔT. If ΔT is maintained and if the device is connected to an electrical load, power is generated.

If, instead, the device is connected to a dc source (as shown in Fig. 2), heat will be absorbed at one end of the TE module, cooling it while heat is rejected at the other end, where the temperature increases. Reversing the current flow reverses the flow of heat, so the module can generate electric power or, depending on how it is connected to external circuitry, heat or cool an object.

Thermoelectric heat pumps have found use in a wide range of applications, including the following, for which other cooling and heating methods are undesirable:

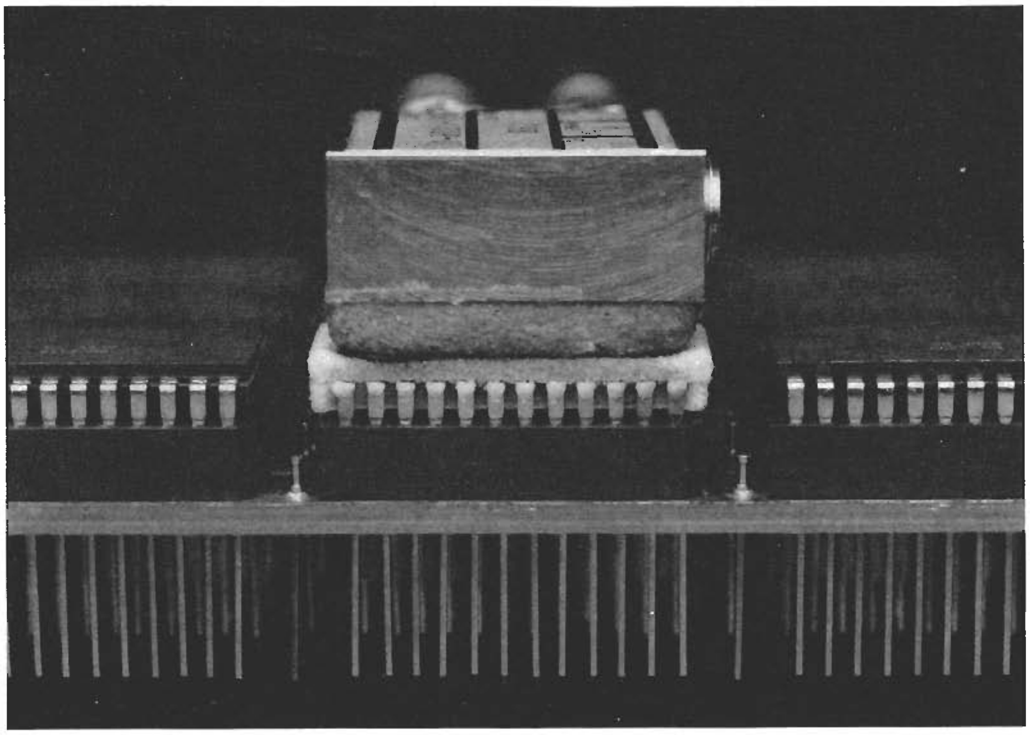
- Controlling temperature-sensitive electronic parameters such as noise or bias current in instrumentation operational amplifiers.
- Cooling infrared and charge-coupled-device detectors.
- Maintaining sample temperatures in medical and laboratory instruments.
- Laser-tuning through temperature control.
- Cooling photomultiplier tubes.
- Semiconductor testing (hot and cold wafer-holding chucks).
- Cooling microprocessors and other devices operating in industrial environments that have high ambient temperature.

Figures 3 and 4 illustrate some of these applications.

Smooth control

Because they can be proportionally managed by a control system that smoothly varies input current or voltage, TE devices provide a unique tool for stabilizing component temperatures in widely varying ambients. Also, in contrast to electromechanical cooling systems with on/off actuators, proportionally or servo-run TE modules allow tighter stabilization of both thermal and electric variations and transients.

Furthermore, the units can operate at up to 150°C or



3. Device cooling. Thermoelectric devices can cool electronic components to control critical parameters such as noise or bias current. In the photo, a TE module is used to cool a critical integrated circuit on a pc board. Note the accumulation of frost on this IC.

higher, even in a vacuum. Compared with electromechanical cooling systems, the solid-state modules combine reduced size and weight with long-term reliability approaching that of other solid-state devices.

One of the better ways of designing in a TE module is to work with parametric performance curves such as those shown in Fig. 5. These transfer functions relate all the important input and output parameters of the module, including operating current, heat absorbed at the cold side, the temperature difference between the hot and cold sides (ΔT), and the module's thermoelectric efficiency.

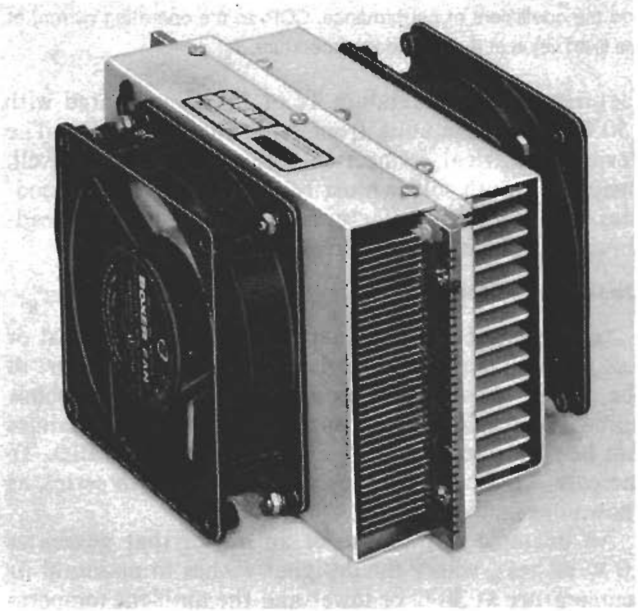
In Fig. 2a, Q_c represents the heat in watts absorbed at the cold side of the TE couple and Q_h is the heat in watts rejected at the hot side. ΔT is the temperature difference between the hot and cold sides. A coefficient of performance (COP) is defined as the ratio of Q_c to electrical power in. Since the TE device uses electrical power primarily to transport rather than generate heat, under some circumstances COP can even exceed 100%.

Figure 5 illustrates the performance graph for a typical module at a fixed hot-side temperature of $T_h = 50°C$. One set of curves relates Q_c to electrical input current, I, at various values of ΔT. The other set of curves relates COP to I, again at various temperature differences.

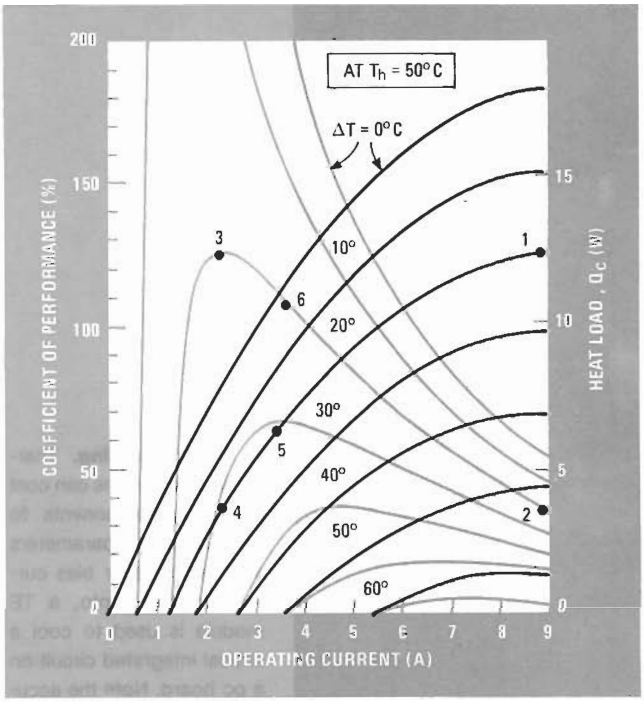
These curves illustrate several important aspects of TE operation. First, it should be noted that temperature differences between hot and cold sides of up to 60°C can routinely be obtained. However, as the temperature difference increases, both Q_c and COP decrease. In optimally adapting TE performance to particular applications, the designer can use these performance curves in a variety of ways. Several design examples are discussed below.

Specification curves from competing manufacturers are not always directly comparable. For instance, some manufacturers evaluate their device performance in a vacuum instead of air. Under these conditions, maximum ΔT can be 10% to 15% higher. Similarly, mounting conditions during test should be carefully compared. If the TE module is soldered to the test fixture heat sink, it will perform better than it does with a thermal grease and a mechanically clamped mounting.

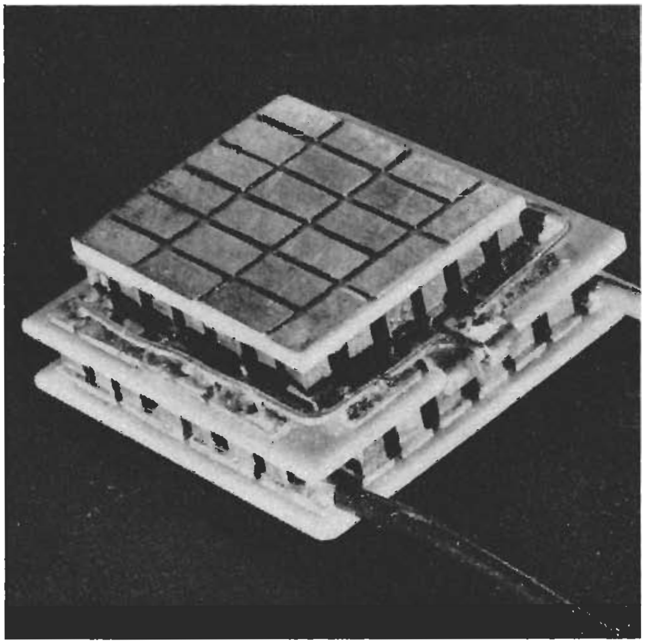
Operating temperature ranges of competing devices also tend to vary. Standard modules from some manu-



4. Cool instruments. Air-to-air thermoelectric heat exchanger cools interior of sealed electronic instrument cabinet. Exchanger is mounted through cabinet wall with its cold side facing the interior. TE modules are sandwiched between two heat sinks.



5. Thermal performance curves. A typical thermoelectric module's performance curve relates the heat absorbed at the cold side, Q_c, and the coefficient of performance, COP, to the operating current at the fixed value of the hot-side temperature, T_h.



6. Cascade. TE modules can be connected thermally in series to increase ΔT. The copper pads visible on the top of the module allow modules to be thermally connected by soldering. These copper pads are not electrically connected to the semiconductor elements below.

facturers have a maximum T_h of 110°C compared with 150°C for similar units from other manufacturers. The devices' electrical connection techniques differ as well. Special bismuth solder must be used to connect to modules from some manufacturers, whereas standard lead-tin solder suffices for other manufacturer's modules.

Design example

TE cooling becomes attractive when 200 W of heat or less must be pumped in applications where some part of the system has to be cooled to temperatures below ambient. To increase heat pumping capacity, TE modules can be connected side by side, thermally in parallel. To increase ΔT they can be cascaded thermally in series, as shown in Fig. 6.

An example is the case of an object that generates 10 W of heat, where the designer wishes to maintain its temperature at 30°C or lower and the ambient temperature is 40°C. Referring back to Fig. 2a, heat must be actively pumped from the object that is to be cooled to the heat sink by the TE module. T_h, the temperature of the heat sink, is higher than T_a, the ambient air temperature. Therefore, the heat the module sends onto the sink will flow out into the ambient by natural (or forced) convection.

As a first step in solving any TE design problem, the designer should calculate the total heat load, Q_C, considering both active heating sources and a phenomenon known as heat leak. Active heating sources are components on the cold surface that generate heat—those that dissipate electrical power, for example. Heat leak is defined as the passive absorption of heat into the cold surface from the warmer surrounding ambient and often represents a significant portion of the total heat load.

Calculating heat leak is a complicated procedure, in which the TE manufacturer's applications department can offer assistance to the user. The major factors involved in calculating heat leak are the temperature difference between the ambient and the object being cooled, the object's surface area, and the thickness of its surface insulation.

In general, heat leak is inversely proportional to insulation thickness (as insulation thickness doubles, heat leak is halved). In contrast, heat leak is linearly proportional to the cooled object's surface area. As surface area increases, heat leak increases linearly.

The slope of the increase depends mainly upon the magnitude of the temperature difference ($T_a - T_c$). For instance, with a 1-in. polyurethane insulation and a temperature difference of 10°C, heat leak increases at a rate of 22 W/1,000 in.^{2} of surface area. With a temperature difference of 70°C, the rate is 73 W/1,000 in.^{2} of surface area.

Total heat load, then, is the sum of the active heat sources and heat leak. This example assumes active generation of 10 W and a heat leak of 2 W, for a total heat load of 12 W. Total heat load is designated Q_{cT}.

Next, a designer must determine the required heat-sink temperature. Selecting a base temperature, T_h, determines the size and type of heat sink needed as well as the number of TE modules necessary to handle the heat load. As T_h moves closer to the ambient air temperature, T_a, fewer modules and less electrical input power are required, though a larger and more effective heat sink is needed.

In this example, the heat-sink base temperature is 10°C above ambient, or T_h = 50°C. Then T_h = 50°C; T_c = 30°C or lower; ΔT = 20°C; and Q_{cT} = 12 W.

To complete the design the following parameters must be determined: input current, I; input voltage, V; input power, P; heat rejection, Q_h; the number of TE modules that are necessary; and the heat sink required.

A designer has several choices in this example. He can design for maximum Q_c (heat absorbed) per module, minimizing the number of modules required. He can maximize COP, minimizing electrical input power. Or he can do a compromise or practical design. The table summarizes the results of these three approaches for the example under discussion.

Maximizing heat absorption

The first approach is designing for maximum Q_c per module and therefore for a minimum number of modules. From the performance curves of Fig. 6, with $\Delta T = 20^\circ C$, a maximum Q_c of 12.5 W occurs at $I = 9$ amperes (point 1 on the curves). Since 12.5 W exceeds the required Q_{cT} of 12 W, only one module will be needed.

With $\Delta T = 20^\circ C$ and $I = 9$ A, COP is 40% (point 2 on the curves). The designer can then calculate power input as:

$$P = Q_c/\text{COP} = 12.5/0.40 = 31.3 \text{ W}$$

Input voltage becomes:

$$V = P/I = 31.3/9 = 3.5 \text{ V}$$

Heat rejected at the hot side of the TE module, Q_h, is the sum of Q_c and electrical power dissipated by the module, P, or:

$$Q_h = Q_c + P = 12.5 + 31.3 = 43.8 \text{ W}$$

Finally, the required thermal resistance of the heat sink is found from:

$$\theta = (T_h - T_a)/Q_h = 10^\circ C/43.8 \text{ W} = 0.23^\circ C/\text{W}$$

Maximizing COP

As a second alternative, the designer can choose to maximize COP, which minimizes the electrical input power required and reduces the heat sink requirements, increasing the required thermal resistance.

From the curves of Fig. 6, for a ΔT of $20^\circ C$, a maximum COP of 125% is found at $I = 2.3$ A (point 3 on the curves). The corresponding Q_c is 3.3 W (point 4 on the curves).

The number of modules required to meet the total heat pumping capacity of 12 W, Q_{cT}, is:

$$N = Q_{cT}/Q_c \text{ (per module)} = 12 \text{ W}/3.3 \text{ W} = 3.6$$

Therefore, four modules will be needed. Next, the total electrical power is calculated as:

$$P = (Q_c \text{ [per module]}/\text{COP})(N) = (3.3/1.25)4$$
$$= 10.6 \text{ W}$$

When the four modules are connected in series, the input voltage becomes:

$$V = P/I = 10.6/2.3 = 4.6 \text{ V}$$

Heat rejection from the four modules is calculated as:

$$Q_h = Q_c \text{ (per module)} \times N + P = 3.3 \times 4 + 10.6$$

SUMMARY OF RESULTS FOR THREE THERMOELECTRIC DESIGN ALTERNATIVES

Parameter	Maximum power dissipation	Maximum coefficient of performance	Practical design
Input current, I (A)	9	2.3	3.4
Input voltage, V (V)	3.5	4.6	3.6
Input power, P (W)	31.3	10.6	12.4
Heat rejection, Q_h (W)	43.8	23.8	25.4
Number of TE modules	1	4	2
Required heat-sink thermal conductivity (°C/W)	0.23	0.42	0.39

$$Q_h = 23.8 \text{ W}$$

Finally, the heat sink's required thermal resistance, θ, is found from:

$$\theta = T_h - T_a/Q_h = 10^\circ C/23.8 \text{ W} = 0.42^\circ C/\text{W}$$

Practical design

In the final approach, the designer may wish to compromise between the preceding alternatives in order to accommodate some other system constraint such as voltage, current, or space availability.

For example, space constraints may allow the use of no more than two modules. Each of the modules must therefore pump at least half of Q_{cT}:

$$Q_c = Q_{cT}/N = 12 \text{ W}/2 = 6 \text{ W}$$

With a ΔT of $20^\circ C$ and a Q_c per module of 6.5 W (and a 0.5-W design margin), the curves of Fig. 6 predict 3.4-A operation (point 5 on the curves). At 3.4 A and a ΔT of $20^\circ C$, COP is found to be 105%.

The total electrical power consumed by the module is:

$$P = (Q_c/\text{COP})\, N = (6.5/1.05)2 = 12.4 \text{ W}$$

With two modules connected electrically in series:

$$V = P/I = 12.4/3.4 = 3.6 \text{ V}$$

Total heat rejection is then calculated as:

$$Q_h = Q_c \times N + P = 6.5 \times 2 + 12.4 = 25.4 \text{ W}$$

Finally, the heat sink's required thermal resistance is found from:

$$\Theta = (T_h - T_a)/Q_h = 10^\circ C/25.4 = 0.39^\circ C/\text{W}$$

Mechanically, thermoelectric modules are only as strong as the semiconductor materials used in their fabrication. These units should never be designed as the mechanical supporting members of an assembly, since stress can damage them.

TE modules can be mounted in various ways. They can be clamped between a heat sink and the object to be cooled, or epoxied or soldered to a heat sink. Mechanical clamping generally gives a more versatile mounting, but soldering offers a better thermal connection.

In general, mounting surfaces should have a flatness of better than ±0.001 in. Furthermore, when mounting several modules side by side, their thicknesses should match to within 0.002 in. ☐