17. Thermoelectric Cooling

17.1 Historical Background

Although commercial thermoelectric modules were not available until almost 1960, the physical principles upon which modern thermoelectric coolers are based actually date back to the early 1800s.

The first important discovery relating to thermoelectricity occurred in 1821 when German scientist Thomas Seebeck found that an electric current would flow continuously in a closed circuit made up of two dissimilar metals, provided that the junctions of the metals were maintained at two different temperatures. Seebeck did not actually comprehend the scientific basis for his discovery, however, and falsely assumed that flowing heat produced the same effect as flowing electric current.

In 1834, a French watchmaker and part-time physicist, Jean Peltier, while investigating the Seebeck Effect, found that there was an opposite phenomenon where by thermal energy could be absorbed at one dissimilar metal junction and discharged at the other junction when an electric current flowed within the closed circuit. Twenty years later, William Thomson (eventually known as Lord Kelvin) issued a comprehensive explanation of the Seebeck and Peltier Effects and described their relationship. At the time, however, these phenomena were still considered to be mere laboratory curiosities and were without practical application.

In the 1930s, Russian scientists began studying some of the earlier thermoelectric work in an effort to construct power generators for use at remote locations throughout their country. This Russian interest in thermoelectricity eventually caught the attention of the rest of the world and inspired the development of practical thermoelectric modules. Today's thermoelectric coolers make use of modern semiconductor technology in which doped semiconductor material takes the place of the dissimilar metals used in early thermoelectric experiments. The Seebeck, Peltier and Thomson effects, together with several other phenomena, form the basis of functional thermoelectric modules.

17.2 Introduction

Thermoelectric are based on the Peltier Effect, The Peltier Effect is one of the three thermoelectric effects; the other two are known as the Seebeck Effect and Thomson Effect. Whereas the last two effects act on a single conductor, the Peltier Effect is a typical junction phenomenon.

Thermoelectric coolers are solid state heat pumps used in applications where temperature stabilization, temperature cycling, or cooling below ambient are required. There are many products using thermoelectric coolers, including CCD cameras (charge coupled device), laser diodes, microprocessors, blood analyzers and portable picnic coolers. This article discusses the theory behind the thermoelectric cooler, along with the thermal and electrical parameters involved.

Seebeck Effect

The conductors are two dissimilar metals denoted as material A and material B. The junction temperature at A is used as a reference and is maintained at a relatively cool temperature (T_C). The junction temperature at B is used as temperature higher than temperature T_C. With heat applied to junction B, a voltage (E_{out}) will appear across terminals T_1 and T_2 and hence an electric current would flow continuously in this closed circuit. This voltage as shown in Figure 17.1, known as the Seebeck EMF, can be expressed as

$$E_{out} = \alpha (T_H - T_C) \qquad (17.1)$$

Where:

- $\alpha = dE / dT = \alpha_A - \alpha_B$
- α is the differential Seebeck coefficient or (thermo electric power coefficient) between the two materials, A and B, positive when the direction of electric current is same as the direction of thermal current, in volts per ^oK.
- E_{out} is the output voltage in volts.
- T_H and T_C are the hot and cold thermocouple temperatures, respectively, in ^oK.

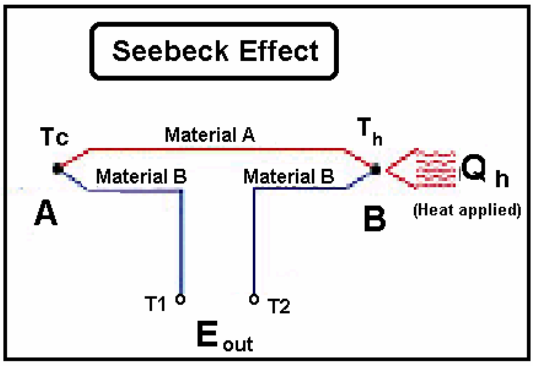


Figure 17.1 Seebeck effect

Peltier Effect

Peltier found there was an opposite phenomenon to the Seebeck Effect, whereby thermal energy could be absorbed at one dissimilar metal junction and discharged at the other junction when an electric current flowed within the closed circuit.

In Figure 17.2, the thermocouple circuit is modified to obtain a different configuration that illustrates the Peltier Effect, a phenomenon opposite that of the Seebeck Effect. If a voltage (Ei_n) is applied to terminals T_1 and T_2, an electrical current (I) will flow in the circuit. As a result of the current flow, a slight cooling effect (Q_C) will occur at thermocouple junction A (where heat is absorbed), and a heating effect (Q_H) will occur at junction B (where heat is expelled). Note that this effect may be reversed whereby a change in the direction of electric current flow will reverse the direction of heat flow. Joule heating, having a magnitude of I^2 x R (where R is the electrical resistance), also occurs in the conductors as a result of current flow. This Joule heating effect acts in opposition to the Peltier Effect and causes a net reduction of the available cooling. The Peltier effect can be expressed mathematically as

$$Q_C \text{ or } Q_H = \beta \times I \qquad (17.2)$$
$$= (\alpha T) \times I$$

Where:

- β is the differential Peltier coefficient between the two materials A and B in volts.
- I is the electric current flow in amperes.
- Q_C and Q_H are the rates of cooling and heating, respectively, in watts.

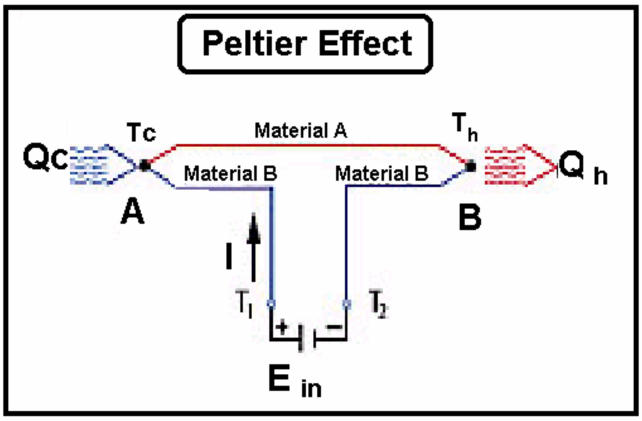


Figure 17.2 Peltier effect

Peltier coefficient β has important effect on Thermoelectric cooling as following:

a) β <0 ; Negative Peltier coefficient

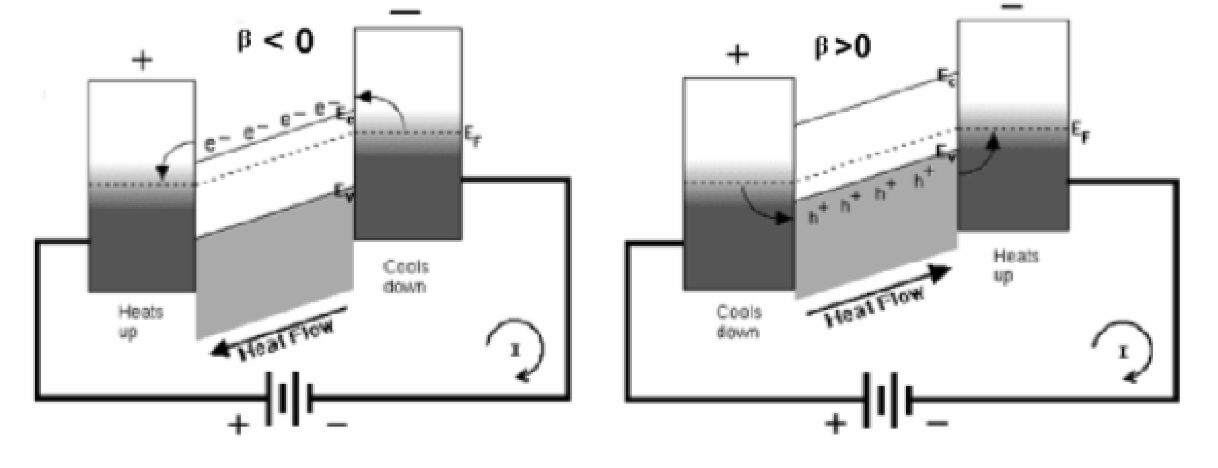
High energy electrons move from right to left.

Thermal current and electric current flow in opposite directions

b) β >0 ; Positive Peltier coefficient

High energy holes move from left to right.

Thermal current and electric current flow in same direction



a) -ve Peltier coefficient b)+ve Peltier coefficient

Figure 17.3 Effect of Peltier coefficient on cooling Process

<u>Thomson Effect</u>

William Thomson, who described the relationship between the two phenomena, later issued a more comprehensive explanation of the Seebeck and Peltier effects. When an electric current is passed through a conductor having a temperature gradient over its length, heat will be either absorbed by or expelled from the conductor. Whether heat is absorbed or expelled depends on the direction of both the electric current and temperature gradient. This phenomenon is known as the Thomson Effect.

17.3 Thermoelectric Principle of Operation

The typical thermoelectric module is manufactured using two thin ceramic wafers with a series of P and N doped bismuth-telluride semiconductor material sandwiched between them as shown in Figure 17.4. The ceramic material on both sides of the thermoelectric adds rigidity and the necessary electrical insulation. The N type material has an excess of electrons, while the P type material has a deficit of electrons. One P and one N make up a couple, as shown in Figure 17.5. The thermoelectric couples are electrically in series and thermally in parallel. A thermoelectric module can contain one to several hundred couples.

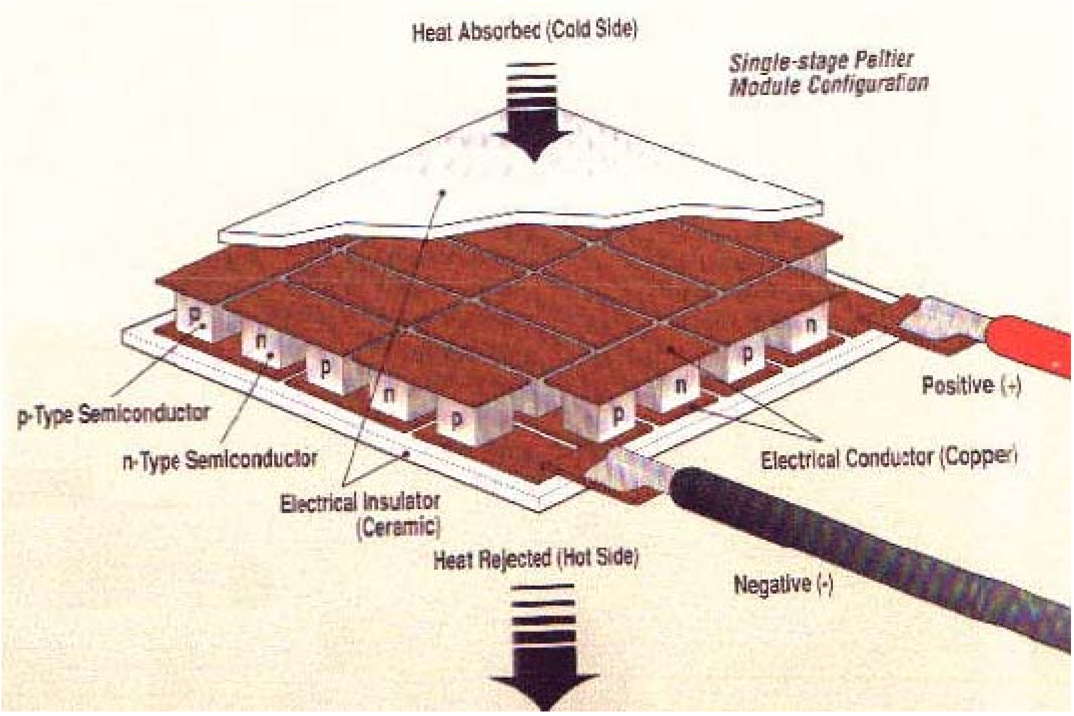


Figure17. 4 TEC Principle of operation

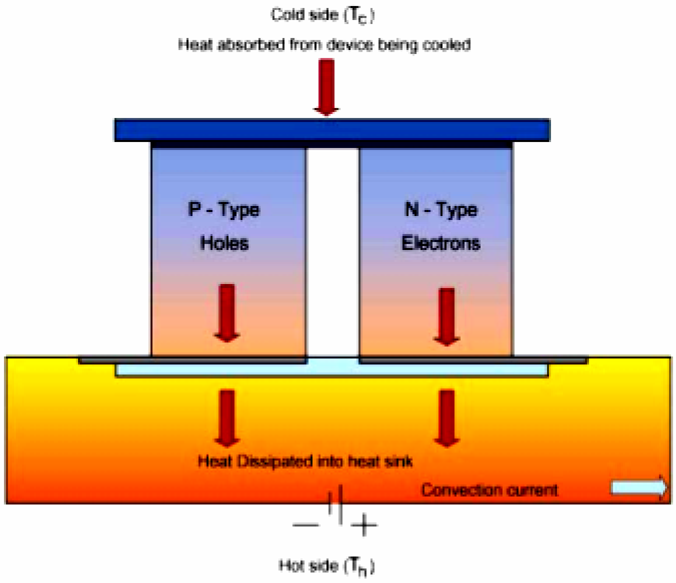


Figure 17.5 Cross section of a thermoelectric cooler

As the electrons move from the P type material to the N type material through an electrical connector, the electrons jump to a higher energy state absorbing thermal energy (cold side). Continuing through the lattice of material; the electrons flow from the N type material to the P type material through an electrical connector dropping to a lower energy state and releasing energy as heat to the heat sink (hot side).

Thermoelectric can be used to heat and to cool, depending on the direction of the current. In an application requiring both heating and cooling, the design should focus on the cooling mode. Using a thermoelectric in the heating mode is very efficient because all the internal heating (Joulian heat) and the load from the cold side is pumped to the hot side. This reduces the power needed to achieve the desired heating.

17.4 Thermal Analysis and Parameters Needed

The appropriate thermoelectric for an application, depends on at least three parameters. These parameters are the hot surface temperature (T_h), the cold surface temperature (T_c), and the heat load to be absorbed at the cold surface (Q_C).

The hot side of the thermoelectric is the side where heat is released when DC power is applied. This side is attached to the heat sink. When using an air cooled heat sink (natural or forced convection) the hot side temperature and its heat transferred can be found by using Equations 17.3 and 17.4.

$$T_h = T_{amb} + \theta\, Q_h \qquad (17.3)$$

Where:

- T_h = the hot side temperature (°C).
- T_{amb} = the ambient temperature (°C).
- θ = Thermal resistance of heat exchanger (°C/watt).

And

$$Q_h = Q_C + P_{in} \qquad (17.4)$$

$$COP = Q_C / P_{in} \qquad (17.5)$$

Where:

- Q_h = the heat released to the hot side of the thermoelectric (watts).
- Q_C = the heat absorbed from the cold side (watts).
- P_{in} = the electrical input power to the thermoelectric (watts).
- COP = coefficient of performance of the thermoelectric device, typically is between 0.4 and 0.7 for single stage applications.

Estimating Q_C, the heat load in watts absorbed from the cold side is difficult, because all thermal loads in the design must be considered. Among these thermal loads are:

1. <u>Active:</u>

i. I^2R heat load from the electronic devices

ii. Any load generated by a chemical reaction

2. <u>Passive:</u>

i. Radiation (heat loss between two close objects with different temperatures)

ii. Convection (heat loss through the air, where the air has a different temperature than the object)

iii. Insulation losses

iv. Conduction losses (heat loss through leads, screws, etc.)

v. Transient load (time required to change the temperature of an object)

By energy balance across the hot and cold junction it produces

$$Q_h = (\alpha\, T_h) \times I - C\,(T_h - T_c) + I^2 R/2 \qquad (17.6)$$

$$Q_C = (\alpha\, T_c) \times I - C\,(T_h - T_c) - I^2 R/2 \qquad (17.7)$$

$R = R_A + R_B$
$C = (k_A + k_B)\,(A/L)$

To get the max the heat absorbed from the cold side (Q_C); by differentiate the Q_c to the electric current I,

$$d\,Q_c / d\,I = 0$$

Then it produces

$$I_{opt.} = \alpha\, T_c / R$$

Substitute for $I_{opt.}$ In Equation 17.7 to get the max the heat absorbed from the cold side

$$Q_C\,(max) = [(Z\, T_c^2)/2 - (T_h - T_c)]\, C \qquad (17.8)$$

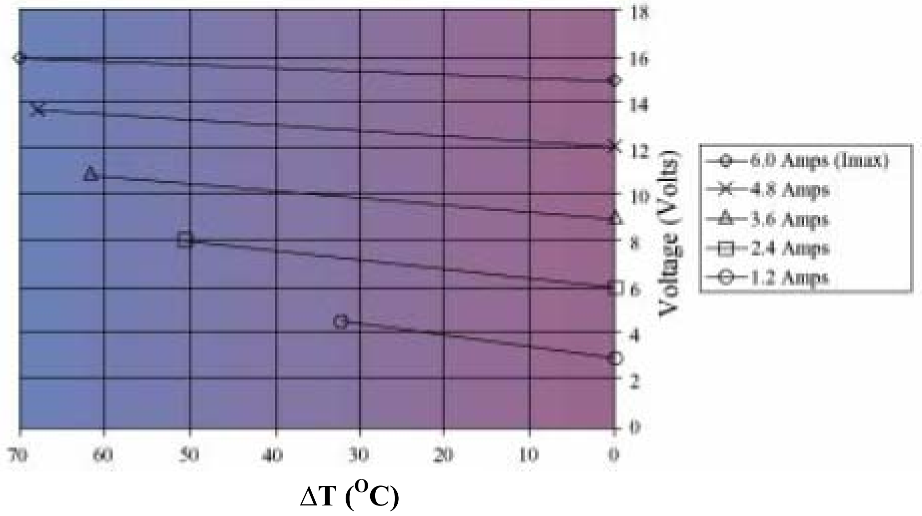
Where:
Z = Figure of merit for the material A and B
$= \alpha^2 / R\,C$

The cold side of the thermoelectric is the side that gets cold when DC power is applied. This side may need to be colder than the desired temperature of the cooled object. This is especially true when the cold side is not in direct contact with the object, such as when cooling an enclosure.

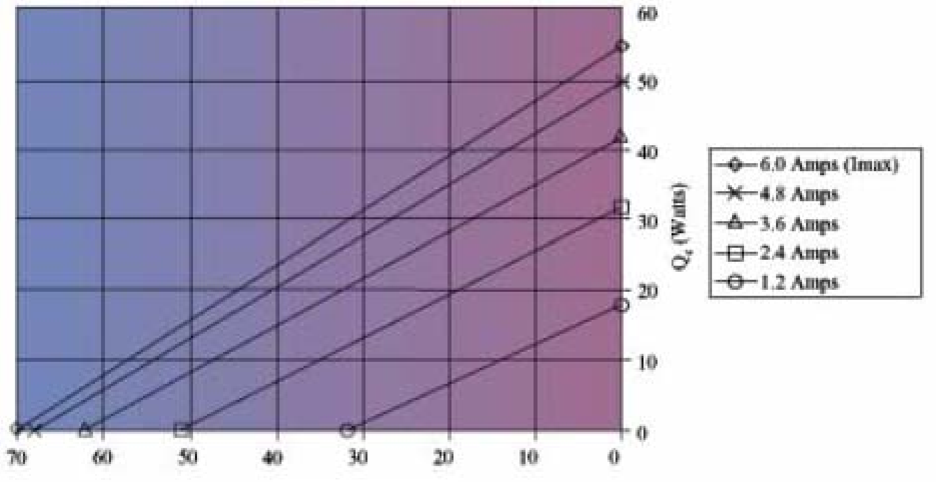
The temperature difference across the thermoelectric (ΔT) relates to T_h and T_c according to Equation 17.9.

$$\Delta T = T_h - T_c \qquad (17.9)$$

The thermoelectric performance curves in Figures 17.6 and 17.7 show the relationship between ΔT and the other parameters.



Figures 17.6 Performance curve (ΔT vs. Voltage)



ΔT (°C)

Figures 17.7 Performance curve (ΔT vs. Q_C)

Example:

A thermoelectric cooling system is to be designed to cool a PCB through cooling a conductive plate mounted on the back surface of the PCB. The thermoelectric cooler is aimed to maintain the external surface of the plate at 40 °C, when the environment is 48 °C. Each thermoelectric element will be cylindrical with a length of 0.125 cm and a diameter of 0.1 cm. The thermoelectric properties are:

	p	n
α (V/K)	170×10^{-6}	-190×10^{-6}
ρ (Ω.cm)	0.001	0.0008
k (W/cm K)	0.02	0.02

Assume the cold junction at 38 °C and the warm junction at 52 °C, and the electrical resistance of the leads and junctions = 10 % of the element resistance and design for maximum refrigeration capacity. If 10 W are being dissipated through the plate and steady-state conditions then

Determine:

1- Number of couples required.
2- Rate of heat rejection to the ambient.
3- The COP.
4- The voltage drop across the d.c. power source.

Solution:

T_h = 52 °C = 325 K
T_c = 38 °C = 311 K
d = 0.1 cm
L = 0.125 cm
$A = (\pi/4)(0.1)^2 = 7.854 \times 10^{-3}$ cm²

Overall electric resistance (R) $= R_{element} + R_{junction}$

$$= 1.1\, R_{element}$$
$$= 1.1(\rho_p + \rho_n)\,(L/A)$$
$$= 1.1\,(0.001 + 0.0008)\,(0.125 / 7.854 \times 10^{-3})$$
$$= 0.0315\ \Omega$$

Conduction coefficient (C) = $(k_p + k_n)$ (A/L)
= (0.02 + 0.02) (7.854 x 10^{-3} /0.125)
= 2.513 x 10^{-3} W/K

Figure of merit (Z) = $(\alpha_p - \alpha_n)^2$/ RC
= (360 x $10^{-6})^2$/ (0.0315 x 2.513 x 10^{-3})
= 1.636 x 10^{-3} K^{-1}

1- Number of couples required.

$Q_C = Q_C$ (max) = N C [$(Z\,T_c^2)/2 - (T_h - T_c)$]
10 = N (2.513 x 10^{-3}) [0.5 (1.636 x 10^{-3} x $(311)^2$) – (14)]
N ≈ 62 couples

2- Rate of heat rejection to the ambient (Q_h).

$I_{opt.} = (\alpha_p - \alpha_n)\, T_c /R$
= (360 x 10^{-6}) x 311/ 0.0315
= 3.55 A

Then

Q_h = N [$(\alpha_p - \alpha_n)\, T_h$ x $I_{opt} - C\,(T_h - T_c) + I^2_{opt}\, R/2$]
= 62 [(360 x 10^{-6}) 325 x 3.55 - 2.513 x 10^{-3} (14) + $(3.55)^2$ 0.0315/2]
= 35.8 W

3- The COP.

COP = Q_C / P_{in}

P_{in} (Power input by power source to the thermoelectric) = Q_h - Q_C
= 35.8 – 10 = 25.8 W

COP = 10 / 25.8
= 0.386

4- The voltage drop across the d.c. power source.

The voltage drop (ΔV) = P_{in} / I
= 25.8 / 3.55
= 7.27 volt

17.5 Powering the Thermoelectric

All thermoelectric are rated for I_{max}, V_{max}, Q_{max}, and ΔT_{max}, at a specific value of T_h. Operating at or near the maximum power is relatively inefficient due to internal heating (Joulian heat) at high power. Therefore, thermoelectric generally operate within 25% to 80% of the maximum current. The input power to the thermoelectric determines the hot side temperature and cooling capability at a given load.

As the thermoelectric operates, the current flowing through it has two effects:

i. the Peltier Effect (cooling)

ii. The Joulian Effect (heating). The Joulian Effect is proportional to the square of the current. Therefore, as the current increases, the Joule heating dominates the Peltier cooling and causes a loss in net cooling. This cut-off defines I_{max} for the thermoelectric.

For each device, Q_{max} is the maximum heat load that can be absorbed by the cold side of the thermoelectric. This maximum occurs at I_{max}, V_{max}, and with $\Delta T = 0°C$. The ΔT_{max} value is the maximum temperature difference across the thermoelectric. This maximum occurs at I_{max}, V_{max} and with no load ($Q_c = 0$ watts). These values of Q_{max} and ΔT_{max} are shown on the performance curve (Figures 17.7) as the end points of the I_{max} line.

17.6 Other Parameters to Consider

The material used for the assembly components deserves careful thought. The heat sink and cold side mounting surface should be made out of materials that have a high thermal conductivity (i.e., copper or aluminum) to promote heat transfer. However, insulation and assembly hardware should be made of materials that have low thermal conductivity (i.e., polyurethane foam and stainless steel) to reduce heat loss.

Environmental concerns such as humidity and condensation on the cold side can be alleviated by using proper sealing methods. A perimeter seal (Figure 17.8) protects the couples from contact with water or gases, eliminating corrosion and thermal and electrical shorts that can damage the thermoelectric module

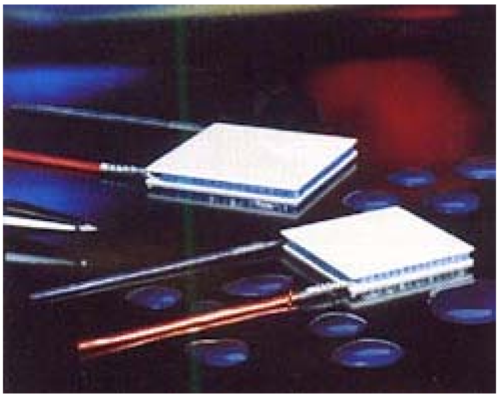


Figure 17.8 Typical thermoelectric with a perimeter seal

The importance of other factors, such as the Thermoelectric's footprint, its height, its cost, the available power supply and type of heat sink, vary according to the application.

17.7 Advantages of Thermoelectric Coolers

Thermoelectric modules offer many advantages including:

- No moving parts
- Small and lightweight
- Maintenance-free
- Acoustically silent and electrically “quiet”
- Heat or cool by changing direction of current flow
- Wide operating temperature range
- Highly precise temperature control (to within 0.1°C)
- Operation in any orientation, zero gravity and high G- levels
- Environmentally friendly
- Sub-ambient cooling

- Cooling to very low temperatures (-80 °C)

17.8 Reliability & Mean Time between Failures (MTBF)

Thermoelectric devices are highly reliable due to their solid state construction. MTBF calculated as a result of tests performed by various customers are on the order of 200,000 to 300,000 hours at room temperature. Elevated temperature (80 °C) MTBF is conservatively reported to be on the order of 100,000 hours.

17.9 Moisture and Vibration Effect

Moisture:

Moisture must not penetrate into the thermoelectric module area. The presence of moisture will cause an electro-corrosion that will degrade the thermoelectric material, conductors and solders. Moisture can also provide an electrical path to ground causing an electrical short or hot side to cold side thermal short. A proper sealing method or dry atmosphere can eliminate these problems.

Shock and Vibration:

Thermoelectric modules in various types of assemblies have for years been used in different Military/Aerospace applications. Thermoelectric devices have been successfully subjected to shock and vibration requirements for aircraft, ordinance, space vehicles, shipboard use and most other such systems. While a thermoelectric device is quite strong in both tension and compression, it tends to be relatively weak in shear. When in a sever shock or vibration environment, care should be taken in the design of the assembly to insure "compressive loading" of thermoelectric devices.

17.10 Comparison: Conventional Refrigeration

Because thermoelectric cooling is a form of solid-state refrigeration, it has the advantage of being compact and durable. A thermoelectric cooler uses no moving parts (except for some fans), and employs no fluids, eliminating the need for bulky piping and mechanical compressors used in vapor-cycle cooling systems.
Such sturdiness allows thermoelectric cooling to be used where conventional refrigeration would fail. In a current application, a thermoelectric cold plate cools radio equipment mounted in a fighter jet wingtip. The exacting size and weight requirements, as well as the extreme g forces in this unusual environment, rule out the use of conventional refrigeration.
Thermoelectric devices also have the advantage of being able to maintain a much narrower temperature range than conventional refrigeration. They can maintain a target temperature to within ±1° or better, while conventional refrigeration varies over several degrees.
Unfortunately, modules tend to be expensive, limiting their use in applications that call for more than 1 kW/h of cooling power. Owing to their small size, if nothing else, there are also limits to the maximum temperature differential that can be achieved between one side of a thermoelectric module and the other.
However, in applications requiring a higher ΔT, modules can be cascaded by stacking one module on top of another. When one module's cold side is another's hot side, some unusually cold temperatures can be achieved

17.11 Thermoelectric Multistage (Cascaded) Devices

A multistage thermoelectric device should be used only where a single stage device does not fill the need.

Given the hot side temperature, the cold side temperature and the heat load, a suitable thermoelectric can be chosen. If ΔT across the thermoelectric is less than 55 °C, then a single stage thermoelectric is sufficient. The theoretical maximum temperature difference for a single stage thermoelectric is between 65 °C and 70 °C.

If ΔT is greater than 55 °C, then a multistage thermoelectric should be considered. A multistage thermoelectric achieves a high ΔT by stacking as many as six or seven single stage thermoelectric on top of each other.

The two important factors are ΔT and C.O.P. should affect on selection of the number of stages. The following Figure 17.9 depicts ΔT, vs. C.O.P.max, vs. Number of stages at T_h = 35 °C.

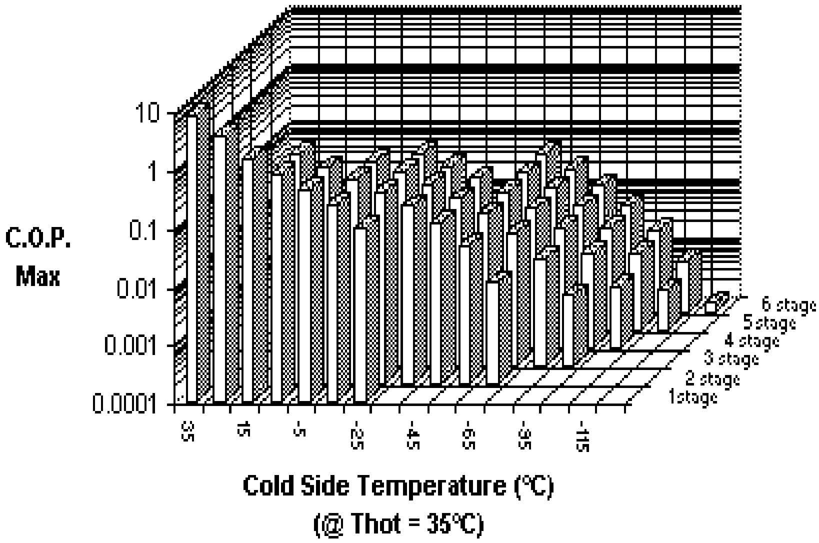


Figure 17.9 ΔT vs. C.O.P. Max as a function of stages

There is another very significant factor that must always be considered and that is the cost. Usually, as the number of stages increase, so does the cost. Certain applications require a trade-off between C.O.P. and cost.

17.12 Summary

Although there are a variety of applications that use thermoelectric devices, all of them are based on the same principle. When designing a thermoelectric application, it is important that all of the relevant electrical and thermal parameters be incorporated into the design process. Once these factors are considered, a suitable thermoelectric device can be selected based on the guidelines presented in this article.