THERMOPILES

Thermopiles and thermocouples are transducers of thermal energy into electrical energy and vice versa. A thermocouple is the basic unit from which thermopiles are constructed and operates on the principles of thermoelectricity. In a closed electric circuit consisting of two dissimilar conductors joined together, electric current flows when the two junctions are maintained at different temperatures. The pair of conductors that make up the circuit are called thermoelements and the electric circuit is called a thermocouple. The open circuit voltage generated in this way is widely used for the accurate measurement of temperature and is schematically illustrated in Fig. 1. For a given pair of conductors, thermoelectric voltage is found to be a function of the temperature difference between the two junctions. In order to measure temperature using a thermocouple, one of the junctions, called the reference junction, is maintained at a fixed reference temperature. In this way, the thermoelectric voltage generated depends only on the temperature of the second junction which is known as the measurement junction. The temperature-voltage relationship for most commonly used thermocouple materials are available in the form of tables, curves, and mathematical equations. For most metals and alloys, thermoelectric voltages generated are very small—of the order of several tens of microvolts per degree Celsius.

If several thermocouples made of the same pair of conductors are connected in series with the alternate junctions at the hot and cold temperatures, respectively, the total output voltage increases by a factor, N, of the number of thermocouples in the circuit. Such a circuit consisting of several thermocouples connected in series is called a thermopile and is shown in Fig. 2. This is a simple way of increasing the output voltage for a given temperature difference and is often used in many practical applications. Thermopiles find widespread use in various applications that include the accurate measurement of temperature, cooling and heating applications, generation of electricity, and infrared radiation detection. Thermoelectric thermometry is widely employed in scientific and industrial temperature measurement and control. When

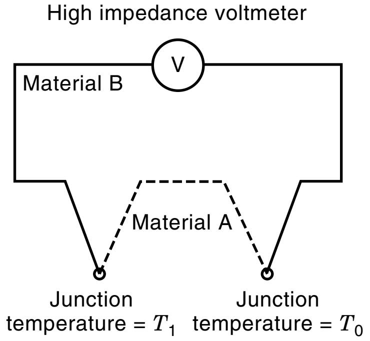

Figure 1. Schematic diagram of a thermocouple circuit consisting of two dissimilar materials A and B with the two junctions at different temperatures T_0 and T_1. The open circuit thermoemf is measured using a high impedance voltmeter.

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

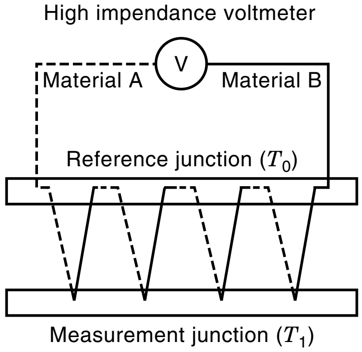

Figure 2. Schematic diagram of a thermopile consisting of four thermocouples connected in series. The alternate junctions of the thermopile are connected to the measurement junction at a temperature T_1 and the reference junction at a temperature T_0.

used in direct thermal contact with the object of interest, thermocouples can measure temperature over a large range from as low as 1 K (−272°C) to as high as 2000°C. This temperature range is further extended when thermopiles are used as the transducer elements in radiation pyrometry. Thermoelectric power generation and thermoelectric cooling are used to a much lesser extent but still dominate some niche applications such as power generation in spacecraft. Recent advances in silicon micromachining technology and thin-film deposition techniques are finding new applications for thermopiles as infrared detectors, accelerometers, and flow sensors.

We begin with a very brief review of thermoelectricity based on a standard thermocouple circuit as shown in Fig. 1. The bulk of this article will, however, concentrate on the various practical applications of thermopiles. A detailed account of thermoelectricity can be found in several excellent books such as Barnard (1) and Pollock (2).

BASIC OF THERMOELECTRICITY

Seebeck Effect

The Seebeck effect can be qualitatively understood by assuming a conductor as being made up of a rigid lattice of atoms in which a gas of free electrons moves under the influence of applied force fields. In the presence of a thermal gradient in such a conductor, electrons at the hot end diffuse toward the cold end. Scattering of electrons by the lattice causes a transfer of some of their energy to the lattice, resulting in the process of thermal conduction. The diffusion of high energy electrons also leads to the build-up of excessive electrons toward the cold end of the conductor and therefore to a build-up of an electric potential which is opposed to the thermal gradient. In this way, a dynamic equilibrium is established between the high energy electrons, being driven toward the cold end by the thermal gradient, and the low energy electrons, being driven toward the hot end by the potential gradient. This electric potential arises whenever there exists a thermal gradient in a conductor and is known as the thermoelectric emf, or electromotive force. It is important to understand that thermoelectric electromotive force (emf) is not a junction potential but instead arises from the interaction of electrons with the lattice within a material in the presence of a thermal gradient.

In order to measure the Seebeck potential, electrical connections to the two ends of the specimen under test are made using a material different from the specimen. Otherwise the symmetry in the circuit will cause no net emf to be detected. The necessary use of two different materials results in the well known configuration of a thermocouple—in which two different conductors are joined together to form the hot and the cold junctions and the open circuit voltage of the couple is measured using a voltmeter. For homogeneous conductors, the thermoelectric emf depends only upon the temperatures of the two junctions and not upon the detailed shapes of the samples or the detailed forms of the temperature distributions along them. The rate of change of thermoelectric emf $V(T)$ with temperature T is known as the absolute thermopower $S(T)$ of the conductor, that is,

$$\frac{\Delta V(T)}{\Delta T} = S(T) \tag{1}$$

For a thermocouple as shown in Fig. 1, the open circuit voltage $V_{AB}(T_0, T_1)$ between the free ends of the thermoelements at temperature T_0 is given by

$$\begin{aligned} V_{\mathrm{AB}}(T_0, T_1) &= V_{\mathrm{A}}(T_0, T_1) - V_{\mathrm{B}}(T_0, T_1) \\ &= \int_{T_0}^{T_1} [S_{\mathrm{A}}(T) - S_{\mathrm{B}}(T)]\, dT \end{aligned} \tag{2}$$

If material B is chosen to be a superconductor and is in its superconducting state (i.e., below the transition temperature), it will make no contribution to V_{AB} and the absolute thermopower of material A, S_A, can be experimentally measured.

In addition to the Seebeck effect, thermoelectricity has a manifestation in two other forms, known as the Peltier and Thomson effects.

Peltier Effect

If an electric current flows across a junction between two dissimilar materials there is a net evolution or absorption of heat in the junction region depending upon the direction of the flow of current. A Peltier coefficient Π_{AB} may be defined as the rate of absorption or evolution of heat per unit current flowing from material A to material B. If dQ_{AB}/dt is the net rate of evolution or absorption of heat at the junction at temperature T, then

$$\frac{dQ_{\mathrm{AB}}(T)}{dt} = \Pi_{\mathrm{AB}} I \tag{3}$$

where I is the current flowing from A to B. Π_{AB} is a function of the junction temperature of the two conductors. For metals, direct measurement of the Peltier coefficient is difficult to perform because of the small amount of heat evolution/absorption associated with the Peltier effect, as well as the difficulty in decoupling the effect from the associated Joule heating and Thomson effect. Instead, it is usually determined using the experimental values of S_{AB} and the Kelvin relations.

Thomson Effect

The Thomson effect relates to the evolution or absorption of heat on the passage of an electric current through a single conductor in the presence of a thermal gradient. Thomson heat is proportional to the product of the current and the thermal gradient. The constant of proportionality is called the Thomson coefficient μ which is defined as the heat generated per second per unit current flow per unit temperature gradient when current flows through a conductor in the presence of a temperature gradient. It is a reversible heat, in the sense that the conductor changes from a Thomson heat absorber to a heat generator when either the direction of the current or the thermal gradient is reversed but not both at the same time. Using arguments based upon equilibrium thermodynamics, Thomson, later called Lord Kelvin, derived the relationship between the Seebeck coefficient, the Peltier coefficient, and the Thomson coefficient. These relations are known as the Kelvin relations and for a material at a temperature T can be written as:

$$\frac{\Pi}{T} = S \tag{4}$$

$$\frac{\mu}{T} = \frac{dS}{dT} \tag{5}$$

These relations allow any two of the thermoelectric effects to be quantitatively calculated if one of either μ or S can be determined over a given range of temperature.

The term "thermoelectric effects" as commonly used refers to all the reversible phenomena which occur at the junctions of dissimilar materials and throughout regions of a material in which finite thermal gradients are present. This is important because passage of current is simultaneously associated with the irreversible phenomena of the evolution of heat ("Joule heating") and the conduction of heat. From a thermodynamic perspective and from Eq. (4), the Seebeck coefficient, S, can be interpreted as the mean transport entropy per unit charge, while Thomson coefficient μ, defined as amount of heat evolved or absorbed within a material per unit current flowing in the presence of a temperature gradient in the material, can be interpreted as the specific heat per unit charge. Thermodynamic perspective of thermoelectric effects is extremely insightful and these arguments were instrumental in the derivation of the Kelvin relations above. However, Lord Kelvin derived these relationships based on the questionable assumptions of reversible thermodynamics, which apparently gave correct results but had to await the developments of irreversible thermodynamics by Onsager in 1931 before these relationshps were finally validated. In order to quantitatively predict the thermopower of a material, a detailed understanding of the electronic behavior of the material is necessary. Nevertheless, the various contributions to thermopower can be understood by remembering that the Seebeck coefficient is related to the electrochemical potential Θ' as:

$$S \propto \frac{1}{e}\frac{\Delta\Theta'}{\Delta T} \tag{6}$$

where e is the charge of the carrier, and T is the temperature. The electrochemical potential,

$$\Theta' = \Theta + e\varnothing \tag{7}$$

includes both the chemical potential (commonly known as Fermi level) Θ, and the electrical potential, $\varnothing$. In a homogeneous material, the chemical potential depends only on the temperature, whereas the quantity $e\Delta\varnothing/\Delta T$) depends on the detailed environment at any given point inside the material. The nature of this electrical environment is determined by the detailed way in which the electrons are scattered by the lattice vibrations, impurities, and other imperfections. In metals and alloys

$$\frac{\partial\Theta}{\partial T} \ll \left| e\frac{\Delta\varnothing}{\Delta T} \right| \tag{8}$$

and the thermopower is primarily determined by the scattering effects. On the other hand, in insulators, the opposite is true and the thermopower is dominated by chemical potential. The magnitude of the electronic thermopower for bulk metals and alloys at high temperatures (above Debye temperature $\approx$ 300 K for most metals and alloys), as given by the free-electron model, Barnard (1), is

$$S = \frac{-\pi^2 k^2 T}{3e}\left[\frac{1}{\Omega}\frac{\partial\Omega}{\partial E} + \frac{1}{l}\frac{\partial l}{\partial E}\right]_{E=E_F} \tag{9}$$

where k is the Boltzmann constant, e the electronic charge, Ω is the area of the Fermi surface, 1 is the electron mean-free-path, and EF is the Fermi energy. Equation (9) implies that thermopower is very sensitive to changes in the electron scattering mechanisms, presence of impurities, strain, and even pressure. It must be emphasized that, although solid state physics gives a broad understanding of the phenomena of thermoelectricity, it has been very difficult to accurately predict the magnitude and occasionally even the sign of the thermopower of metals and alloys. Therefore, for most of the practical thermocouple systems, the dependence of thermoelectric emf on temperature is an empirical relationship.

LAWS OF THERMOCOUPLE CIRCUITS

Based on the thermoelectric effects discussed and using the simple thermocouple circuit shown in Fig. 1, a number of empirical statements can be deduced. These laws are simple restatements of the detailed principles of thermoelectricity and form the basis for the practical construction and applications of thermocouple circuits.

Law of Homogeneous Materials

No thermoelectric voltage can be measured in a thermocouple circuit consisting of chemically and physically identical homogeneous materials no matter what the shape or cross-section of the conductor or the temperature difference between the two junctions. In reality though one must remember that, in the presence of a thermal gradient, thermoelectric voltages might be observed in single material circuits which are very likely to include inhomogenieties such as stressed or oxidized sections of the same material. Thermoelectrically speaking, these sections can be considered as different materials.

Law of Different Materials at a Single Temperature

No thermoelectric voltage can be measured in a thermoelectric circuit consisting of many dissimilar materials and junctions if it is maintained throughout at a constant temperature. This law simply affirms the fact that in the absence of thermal gradients no thermoelectric phenomena can be observed.

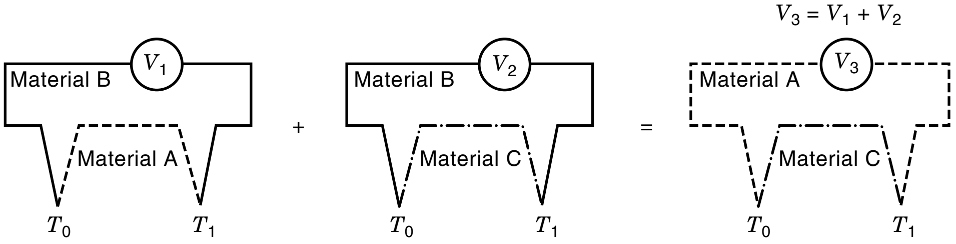

Figure 3. Schematic illustration of the law of different materials at different temperatures. This law is useful in generating the thermocouple calibration chart, the thermoelements of which have been calibrated against a common reference material.

Law of Different Materials at Different Temperatures

For the same junction temperatures, the algebraic sum of the thermoelectric voltages in two circuits composed respectively of materials A–B and B–C is the same as the thermoelectric emf of a single circuit composed of materials A–C. This law is schematically shown in Fig. 3. The main application of this law is in the generation of the temperature–thermoemf relationship for a given thermocouple combination if the temperature–thermoemf relationship of the constituent materials are available with respect to a common reference material such as platinum.

Law of Intermediate Temperatures

For a given two junction thermocouple, if the thermoelectric emf measured is V_1 when the two junctions are at temperatures T_0 and T_1 and V_2 when the two junctions are at temperatures T_1 and T_2, then the thermoelectric emf V_3 produced by the same thermocouple when its junctions are at temperatures T_0 and T_2 is equal to $V_1 + V_2$. This law is particularly important if a thermocouple is intended for use at a different reference junction temperature than that used in its original calibration. This law is schematically illustrated in Fig. 4.

THERMOPILES AND TEMPERATURE SENSORS

As we have already discussed, a thermocouple essentially transforms thermal energy into electrical energy and vice versa. As temperature sensors, thermocouples have the advantages of not requiring any power supply for their operation and can be used over a very large temperature range. However, they have the disadvantages of small output voltages, susceptibility to noise pickup by the thermocouple wires, and relatively high drift. For homogeneous, macroscopic metals and alloys at high temperatures, the laws of thermoelectricity are essentially independent of the physical dimensions of the thermocouple. This means that most thermocouples are constructed from wires as small as is practical or most cost effective. However, small thermocouples are more readily suited for spot measurements of temperature and therefore provide a small physical cross-section to interact with the sensing stimulus.

A thermopile consisting of several thermocouples connected in series not only offers a simple way of increasing the sensing cross-section of the thermocouple but as discussed earlier also offers the possibility of obtaining a larger electrical signal for a given temperature difference. As transducers of thermal energy into electrical energy the two main, Seebeck effect based, applications of thermopiles are as temperature and radiant flux sensors and as generators of electrical power. As transducers of electrical energy into thermal energy using Peltier effect, the main application of thermopiles is as cooling devices or refrigerators. The use of several thermocouples connected in series results in higher sensitivity in sensor applications and higher power in electricity generation applications. In cooling and heating applications, the many thermocouple junctions of thermopiles not only result in more power but can also be set-up into practical configurations for uniform heating and cooling of large surface areas.

The arrangement of connecting several thermocouples in series such that the alternate junctions are at two different temperatures amplifies the thermoelectric voltage of a single thermocouple by the number of thermocouples, N, connected in series.

$$V_{\text{Thermopile}} = N \cdot V_{\text{Thermocouple}} \tag{10}$$

However, this also results in an increase in the noise due to the N-fold increase in the resistance of the device. In an open circuit voltage measurement configuration, the primary source of internal noise in a thermocouple is from the random fluctuation of the charge carriers in the material and is called the Johnson noise. The root mean square (rms) open circuit Johnson noise voltage, V_n, in a 1 Hz bandwidth for a material of resistance R which is at a temperature T is given by

$$V_{\text{n}} = \sqrt{4kRT} \tag{11}$$

where k is the Boltzmann constant. It can be seen that, while the signal from a thermopile increases by a factor of N, the open circuit noise voltage in a thermopile increases by a factor of $\sqrt{N}$, therefore resulting in an effective signal to noise ratio increase of $\sqrt{N}$.

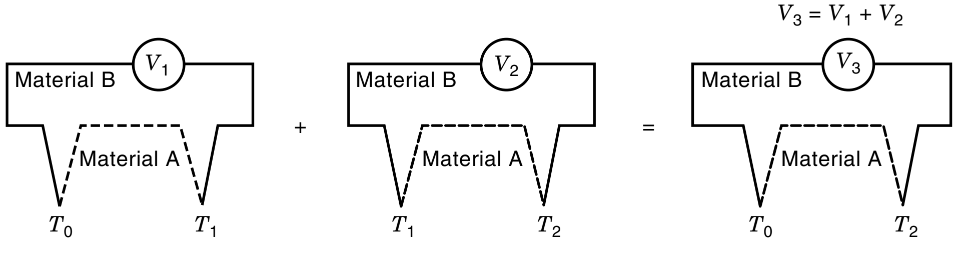

Figure 4. Schematic illustration of the law of intermediate temperatures. This law is mainly used for operating thermocouples at reference temperatures which are different from the standard reference temperature.

Table 1. Seven Standard Types of Thermocouples Used in the Measurement of Temperature

Thermocouple Type	Nominal Composition (% weight)	Useful Temperature Range (°C)	Comments
Type B	(Pt + 30% Rh) vs. (Pt + 6% Rh)	0–1704	Recommended for continuous use in oxidizing and inert atmospheres. Limited vacuum use is possible.
Type E	(Ni + 10% Cr) vs. (Cu + 43% Ni)	−250–871	Primarily for oxidizing atmospheres. Does not corrode at sub-zero temperatures
Type J	Fe vs. (Cu + 43% Ni)	−210–1200	Suitable for vacuum use or where free oxygen is deficient since iron rapidly oxidizes above 538°C (1000F).
Type K	(Ni + 10% Cr) vs. (Ni + 2% Al)	−250–1260	Suitable for continuous use above 538°C in oxidizing atmospheres.
Type R	(Pt + 13% Rh) vs. Pt	−50–1482	Not suitable for reducing atmospheres and for continuous high temperature applications.
Type S	(Pt + 10% Rh) vs. Pt	−50–1482	Not suitable for reducing atmospheres and for continuous high temperature applications.
Type T	Cu vs. (Cu + 43% Ni)	−250–400	High resistance to corrosion from atmospheric moisture or moisture condensation. Can be used in either vacuum, oxidizing, or reducing atmosphere.

Choice of Materials

Based on the material of construction, thermopiles can be broadly classified into two major groups as: (1) metal-alloy thermopiles and (2) semiconductor thermopiles. Metal-alloy thermopiles are mainly used in temperature measurement applications whereas semiconductor thermoelements find applications in power generation, refrigeration, and radiant flux measurements. This is due to the fact that although metals and alloys have a small Seebeck coefficient, typically of the order of a few tens of microvolts per kelvin, they can be very reliably and inexpensively reproduced. Semiconductors on the other hand exhibit superior properties for thermoelectric energy conversion applications with larger Seebeck coefficients, typically of the order of hundreds of microvolts per kelvin. Semiconductor thermoelements are more expensive and can be less easily formed into various convenient forms for temperature measurement applications.

Most commercially available thermocouples and thermopiles used for temperature measurement are made up of metals and alloys. As stated above metals and alloys exhibit very reproducible thermoelectric properties and can be very easily and inexpensively formed into convenient forms such as thin wires suitable for temperature measurements. Additionally, modern potentiometers can measure very low voltages very accurately and reliably. These developments have made it possible to routinely measure temperatures accurately to a fraction of a degree Celsius using standard metallic thermocouples. Although it is possible to measure temperature using any combinations of metals and alloys, only seven combinations of different alloys are commonly used for temperature measurement in the range of 20 K to 2000 K. For each of the seven thermocouple combinations there exist internationally agreed reference tables for thermal emf versus temperature as well as a letter designation. Table 1 lists the type designation of the alloy compositions, their useful temperature range, and the typical application environment for each of the thermocouple types. For a more detailed discussion on the use of thermocouples for temperature measurement refer to the American Society for Testing and Materials (ASTM) manual (3).

Thermoelectric Figure of Merit

The efficiency of energy conversion of thermoelectric devices is not only related to the absolute thermopower of the materials but also to their thermal and electrical conductivity. This can be qualitatively understood, for example, by considering a thermocouple as an electricity generator. In order to achieve high energy conversion efficiencies, the conductive heat losses from the transducing junction through the thermocouple legs need to be minimized (i.e., low thermal conductivity materials are required) and the electrical power output (V^2R) needs to be maximized (i.e., large thermopower and low electrical resistivity materials are required). In fact, thermoelectric figure of merit, Z, for a given material is given by

$$Z = \frac{S^2\sigma}{\kappa} \tag{12}$$

where S is the absolute thermopower of the material, and σ and κ are its electrical conductivity and thermal conductivity, respectively. The thermoelectric figure of merit has the dimensions of inverse of temperature. A more detailed derivation of the thermoelectric figure of merit is based on the maximization of the coefficient of performance of a thermoelectric power generator/refrigerator or the normalized detectivity D^* of an infrared detector. For a more comprehensive treatment of the figure of merit of thermoelectric materials, see references by Rowe and Bhandari (4), Kaye and Welsh (5), or Baltes et al. (6).

Materials with a large value of Z over a large temperature range are required in order to achieve a high energy conversion efficiency. For a thermocouple, the figure of merit can be extended to take into consideration the different material properties of the two materials and is given by

$$Z_{AB} = \frac{S_{AB}^2}{\left(\sqrt{\frac{\kappa_\mathrm{A}}{\sigma_\mathrm{A}}} + \sqrt{\frac{\kappa_\mathrm{B}}{\sigma_\mathrm{B}}}\right)^2} \tag{13}$$

where the subscripts A and B refer to the properties of the two materials constituting the thermocouple respectively. Table 2 lists the thermopower and the figure of merit for some

Table 2. Thermal and Electrical Properties, Including the Seebeck Coefficient and the Thermoelectric Figure of Merit, of Some Metals, Alloys and Semiconductors

Material	$\sigma(\Omega^{-1}\,\mathrm{m}^{-1})$	$S(\mu\mathrm{V/K})$	$\kappa(\mathrm{Wm}^{-1}\mathrm{K}^{-1})$	$Z(\mathrm{K}^{-1})$
Positive Thermoelements				
Cu	6.0×10^{7}	$+1.83$	401	5.01×10^{-7}
Au	4.2×10^{7}	$+1.94$	318	4.97×10^{-7}
Ag	6.3×10^{7}	$+1.50$	429	3.35×10^{-7}
Sb	2.4×10^{6}	$+40.0$	8.00	4.80×10^{-4}
Sb_2Te_3	2.0×10^{5}	$+130$	2.82	1.20×10^{-3}
*$Bi_{0.5}Sb_{1.5}Te_3$	5.9×10^{4}	$+230$	1.05	2.97×10^{-3}
*Polysilicon ($p = 3 \times 10^{19}$)	1.3×10^{4}	$+135$	31.0	7.97×10^{-6}
*$Si_{0.7}Ge_{0.3}$ ($p = 10^{19}$)	8.8×10^{4}	$+121$	5.50	2.33×10^{-4}
Negative Thermoelements				
Al	3.6×10^{7}	-1.70	236	4.41×10^{-7}
Ni	1.3×10^{7}	-19.0	91.0	5.16×10^{-5}
Bi	8.3×10^{5}	-60.0	22.0	1.36×10^{-4}
*Bi_2Te_3	1.2×10^{5}	-210	2.34	2.30×10^{-3}
$Bi_{0.87}Sb_{0.13}$	1.4×10^{5}	-100	3.10	4.55×10^{-4}
Si ($n = 10^{19}$)	2.0×10^{4}	-200	145	5.50×10^{-6}
*Polysilicon ($n = 3 \times 10^{19}$)	1.1×10^{5}	-121	29.4	5.58×10^{-5}
*GaAs ($n = 10^{17}$)	6.7×10^{3}	-390	39.0	2.74×10^{-5}

* Refers to values for thin film materials.

of the commonly used bulk and thin film thermocouple materials respectively.

Standard Construction

The main application of thermocouples and thermopiles is as temperature sensors. As has been discussed earlier, in their most popular use a thermopile is constructed of several thermocouples connected in series. Thermopiles are used for the direct measurement of temperature by placing the measurement junction in intimate thermal contact with the object of interest and the reference junction at a fixed known temperature. The detailed construction of a thermopile depends on the specific application for which it is being used. For most temperature measurement applications, the thermopile configuration that is most practically implemented is a modified form of the thermopile shown in Fig. 2. The measurement junction of the thermopile made of metals A and B, is located at the temperature, T_1, to be measured. The input and output wires of the reference junction are connected to an extension wire C and is maintained at a temperature T_0. The extension wires C finally connect the thermopile to a high impedance voltmeter at room temperature T_R. This configuration occurs invariably in all situations where the temperature to be measured is located remotely as compared to the voltmeter. Summing the various thermoelectric voltages for the circuit we get

$$\mathrm{V} = V_C(T_0, T_R) + N\{V_A(T_0, T_1) - V_B(T_0, T_1)\} - V_C(T_0, T_R) \tag{14}$$

If the two wires made of material C are homogeneous and have the same thermoelectric properties, then the total thermoelectric emf measured is the same as obtained using the thermopile made only of materials A–B. Developments in electronic circuits have led to accurate tracking of the variations in reference junction temperature using thermistors. This is often used to compensate for any errors in the measured temperature caused due to drifts in the temperature of the reference junction.

Thermocouples can also be connected in parallel as shown in Fig. 5. In such a case the parallel thermopile configuration provides a temperature averaging effect. However, extreme care must be taken to prevent the possibility of closed loop currents within the thermocouple pairs which can arise easily due to the variations in the calibration curves of the individual thermocouples, differences in the individual resistance of the thermocouples, and variations in the Seebeck coefficient of the individual thermoelements in the temperature range of measurements. Therefore, in spite of the possibility of temperature averaging, the parallel arrangement of thermocouples in not commonly used.

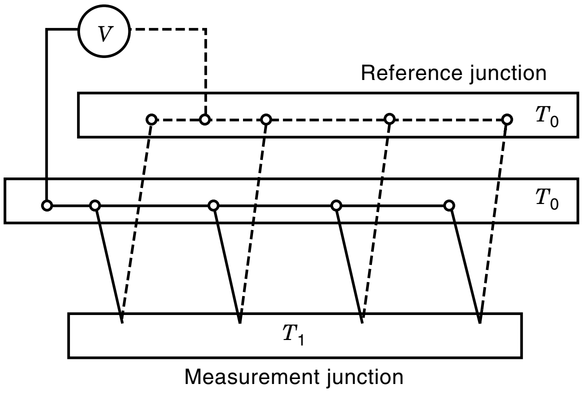

Figure 5. Schematic drawing of a thermopile consisting of four thermocouples connected in electrical parallel configuration. Used with a certain amount of caution, this configuration can be used for temperature averaging.

Reference Junction

As we have already discussed, a thermopile essentially measures the difference in temperature between the two junctions across which it spans. To measure temperature using a thermopile; one of its junctions is maintained at a fixed reference temperature and the temperature of the measurement junction is deduced using the calibration chart of the thermocouple constituting the thermopile. Reference junction serves two functions, namely, (1) as a junction at a standard reference temperature of 0°C for producing the thermocouple voltage-temperature calibration chart or (2) as a junction at a known temperature, other than the reference temperature of 0°C, which is either fixed or variable. The standard reference temperature used in thermocouple calibration is the ice point, or 0°C—the equilibrium temperature between ice and water at 1 atmosphere pressure. Historically, this reference temperature has evolved from the ease of availability of ice and water in the laboratory and its uniqueness in the phase diagram. For a detailed treatment of reference junctions for thermocouple calibration refer to Quinn (7).

The fixed reference temperature of 0°C is good for calibrating thermocouples and thermopiles but is very cumbersome and most often impractical to implement in typical industrial situations. In order to maintain the reference junctions at a constant temperature of 0°C, Peltier coolers, discussed later, are sometimes used. However, it is very difficult to maintain the temperature of the actual cold junctions at this temperature due to the variability in thermal contact and the difficulty of surrounding the reference junction sufficiently to ensure the temperature to the desired accuracy. Therefore, it is desirable to use temperatures other than 0°C for the reference junction. In its most widespread use, the reference junction is normally kept at ambient conditions and its temperature is continuously monitored using a thermistor. In this way, any variations in the temperature of the reference junction are known and electronically compensated.

In using thermopiles to measure temperature, in addition to the errors associated with reference junction, and deviations from standard thermoemf due to thermocouple materials and extension wires, users should also be aware of the possible error sources associated with measurement junctions. These errors can be especially significant when thermopiles are used in the measurement of surface temperatures, since their very presence perturbs the heat transfer characteristics of the surface and changes the temperature distribution. The thermopile wires provide additional heat transfer paths and can effectively lower the actual temperature of the measurement surface. Another major source of error arises from the thermal contact resistance between the surface and the thermopile junction. This thermal contact resistance causes a temperature gradient to be set up between the surface and the thermopile junction and therefore prevents the junction from attaining the surface temperature. The relationship between the measured and true temperature can be expressed as:

$$\zeta = \frac{T_m - T_t}{T_m - T_a} \tag{15}$$

where ζ is called the installation factor, T_m is the measured temperature, T_t is true surface temperature, and T_a is the temperature of the ambient. In addition, errors can also arise in surfaces where temperature gradients exist due to the errors associated with the exact positions of the thermopile junctions relative to the surface. The response time of the thermopiles can also cause errors in the measurement of transient temperature signals.

OTHER APPLICATIONS OF THERMOPILES

Thermopiles are extensively used as the basic transduction elements in many thermal sensors (8). Thermal sensors operate by first converting the input signals (the measurand) into a temperature signal in the sensor element which is subsequently transduced into an electrical signal. The most well-known application of thermopiles as thermal sensors has been for detecting infrared radiation. When used as radiation sensors, the measurement junction of the thermopile is placed in intimate contact with a radiation absorbing structure while the reference junction is attached to a heat sink. Absorption of incident radiation causes a preferential rise in the temperature of the measurement junction and therefore in a thermoemf. Recent advances in silicon micromachining technology have made possible several novel thermopile-based thermal sensors which include accelerometers, calorimeters, and mass flow sensors. A comprehensive review of silicon micromachined sensors is presented by Middelhoek (9), and for an excellent review of thermoelectric microsensors and systems refer to Baltes et al. (6). In addition, thermopiles are also used in heating and cooling applications and in some niche power generation applications. These applications of thermopiles are discussed in detail in the following sections.

Radiation Detectors

The most commonly known physical manifestation of energy is as electromagnetic radiation. Electromagnetic radiation spans a very large spectrum from gamma rays at the high energy end to radio waves at the low energy end. Lying between the visible and microwave parts of the electromagnetic spectrum, infrared radiation is widely used for: noncontact temperature measurements, intrusion alarm systems, remote sensing, astronomy, and heat emission based target detection and tracking. These applications are all possible because heated objects provide an excellent source for infrared radiation which is emitted by virtue of their temperature. The quantity of importance, most often, is the radiant power being emitted by a blackbody or monochromatic source. Excellent reviews on infrared radiation and infrared detectors are available in Smith, Jones, and Chasmar (10) and Keyes (11).

The sensing element of a thermopile infrared detector consists of a very small heat capacity radiation absorbing structure which is thermally isolated from the main sensor body which acts as a heat sink. The measurement junction of the thermopile is thermally attached to the sensing element while, the reference junction is attached to the main body of the sensor. Upon absorption of the incident radiant flux, the sensing element heats up relative to the main body of the sensor and the thermopile generates an open circuit voltage which is calibrated to read the power density. Traditionally, thermopiles were fabricated as bulk material devices by welding together fine wires and thin black radiation absorbers. However, developments in micromachining technology have

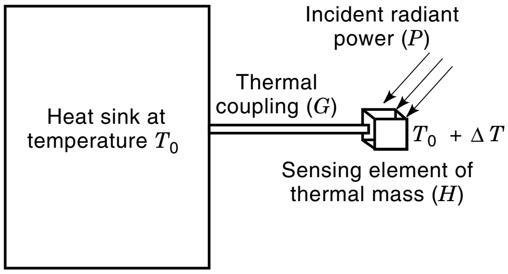

Figure 6. Schematic representation of a sensing element of thermal mass (H), connected to the heat sink at temperature (T_0) via a thermal conductance (G). Absorption of the incident radiation of power (P) causes the temperature of the sensing element to rise to $T + \Delta T$.

made it possible to fabricate thermally isolated structures with small heat capacity while advances in microfabrication techniques have made it possible to fabricate very high density thermopile structures using thin films. These developments have led to the design and construction of a variety of thin-film thermopile radiation detectors covering a wide range of impedance, sensitivity, and time constants (12,13,14,15).

A simple model of a thin-film thermopile is shown in Fig. 6. The detector element of thermal mass H is coupled to the heat sink at a constant temperature T_0 via a thermal conductance G. When a radiant power P is incident on the sensor element, its temperature T is found by solving the equation:

$$\epsilon P = H\frac{\partial T}{\partial t} + G(T - T_0) \tag{16}$$

where ϵ is the emissivity of the sensor element and t is time. For a sinusoidal power input, $P = P_0\exp(i\omega t)$, the steady state solution of Eq. (16) is

$$\Delta T = T - T_0 = \frac{AP_0}{\sqrt{G^2 + \omega^2 H^2}} \tag{17}$$

A characteristic thermal time constant, τ, for the detector can be defined as

$$\tau = H/G \tag{18}$$

From Eq. (17) it can be seen that a high sensitivity, which corresponds to a large ΔT, can be achieved by making G as small as possible and $\omega H \ll G$. In other words, both the heat capacity of the detector element and its thermal coupling to the surroundings should be as small as possible. A small heat capacity for the detector element implies a detector element of as small and light weight a construction as is practically possible whereas the smallest value for G is achieved when the thermal coupling of the sensing element to the heat sink is only through radiative exchange. The design challenge of a thermopile radiation detector, therefore, is the optimization of the interaction of the sensing element (measurement junction) with incident radiation while simultaneously reducing its thermal mass and all other thermal contacts to the surroundings.

Silicon micromachining technology, by the use of precise lithographic patterning and crystallographic etching techniques, has made it possible to fabricate free-standing membranes and structures with very low heat capacity and good thermal isolation (16,17). The measurement junction of such a thermopile is located along the contours of the highest temperatures on the free-standing structure whereas the reference junction is located along the thick rim of the substrate. Figure 7 schematically illustrates a typical micromachined cantilever structure based thermopile. This technology is naturally oriented toward the use of semiconductors and metal thin films as the thermoelements. Fortunately, semiconductors, as we have discussed earlier, are found to have a high thermoelectric figure of merit and make an excellent choice for this technology. To further improve the responsivity and spectral response, these infrared detectors are often coated with absorber materials such as gold black or with infrared absorbing thin films (18,19). Thin-film thermopiles with a responsivity of several tens of volts per watts and a time constant of tens of milliseconds are commercially available. Figure 8 shows a commercial thin film Bi/Sb thermopile infrared

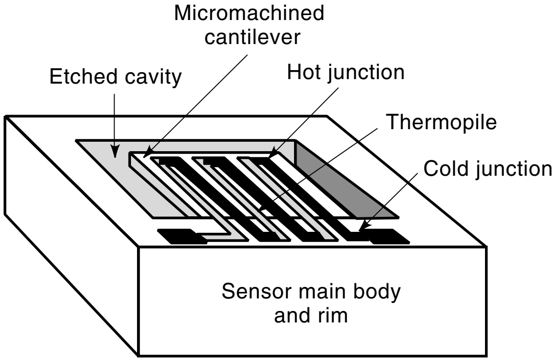

Figure 7. Schematic diagram of a micromachined thermopile infrared detector. The hot junctions of the thermopile (the sensing element) are fabricated on a free-standing cantilever while the cold junctions are thermally attached to the silicon rim which acts as the heat sink. These devices are fabricated using silicon microfabrication techniques along with anisotropic etching of silicon.

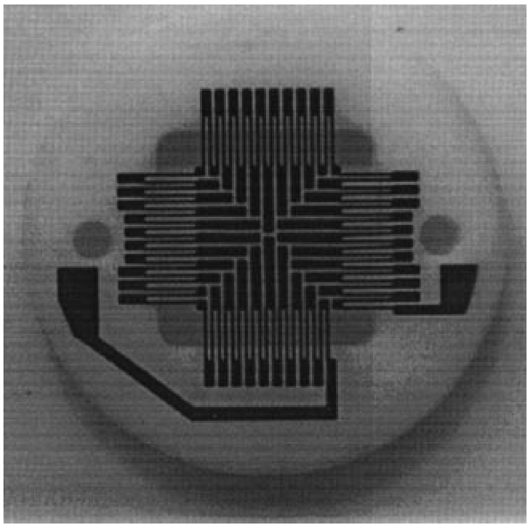

Figure 8. Optical micrograph of a commercial thin film Bi/Sb thermopile infrared detector from Dexter Research Center. The device consists of a 2 mm × 2 mm active area and 40 thermocouple junctions connected in series. The detector has a responsivity of 19.2 V/W and a time constant of 40 ms. (Courtesy: Dexter Research Inc., Michigan.)

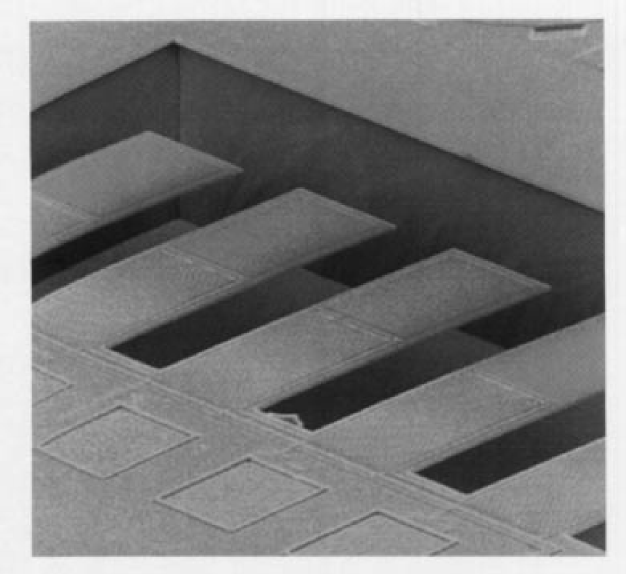

Figure 9. SEM (scanning electron microscope) micrograph of a cantilever beam infrared sensor array. The length of the oxide/nitride cantilever beam is 300 μm, the width is 200 μm and the depth of the etch grove is about 120 μm. The thermopile is made up of n-polysilicon/ p-polysilicon as the thermoelements. (Courtesy Physical Electronics Laboratory, ETH, Zurich, Ref. 14)

detector from Dexter Research Center and Figure 9 shows a typical CMOS (complementary metal-oxide-semiconductor) based polysilicon thermopile. Further reduction in the thermal mass of such sensors has been achieved by completely removing the supporting membranes under the thermoelements. These modifications have reduced the time constants of the infrared detectors to a few microseconds. Such a free-standing copper-constantan microthermopile is shown in Fig. 10. Current efforts in this field are focused on the further optimization of the thermo-mechanical design of the sensing elements (20), utilizing thin film semi-metals and semiconductors as thermoelements and the integration of the sensor with on-chip antenna structures (21). Efforts are also focused on fabricating these devices as planar imaging arrays with integrated CMOS circuitry for signal conditioning and readout (22).

Integrated Thermopiles

The demand for intelligent sensor systems, which has included an increasing number of sensors as well as an increasingly complex analog and digital circuitry, has been the motivation behind the development of integrated microsensors. In particular, thermal sensors are at the heart of several such microsystems. Thermal sensors first convert the measurement signals into a thermal signal, which is then transduced into an electrical signal primarily using thermoelectric or thermoresistive techniques. Thermoresistive elements (thermistors) compete in nearly every application along with thermopiles and are also widely used in sensor applications. This section will limit the discussion only to the use of integrated thermopiles in various microsensor applications. Integrated thermopiles offer the possibility of batch fabricating microsensors and systems at large volumes and low cost with high reliability and thus form a subject of great current interest. Integrated thermopiles fabricated using micromachining technology are used, as the transduction elements, in several thermal microsensors applications which can be broadly classified as: (1) thermomechanical sensors (mass flow sensors, pressure sensors, and accelerometers), (2) thermal converters (electrical power sensors), and (3) thermochemical sensors (calorimeters and reaction enthalpy sensors).

Mass Flow Sensors, Pressure Sensors, and Accelerometers

In a mass flow sensor, a thermally isolated resistor is heated using a constant power. Thermopile sensors are placed along the upstream and downstream of the flow with the resistor heater in between them. The heat transfer coefficient, which is the ratio of the heat flow (from the heater surface to the flowing fluid) and the temperature difference (between the heater surface and the flowing fluid), among other parameters, is a function of the flow velocity. It is larger for the upstream flow than for the downstream flow and therefore induces a temperature difference between the upstream and the downstream thermopiles which is used to detect the flow velocity as well as the flow direction along the line of the sensors (23,24). The heat transfer coefficient is a very sensitive function of the heater and sensor geometry, the nature of fluid flow (laminar, turbulent, and so on), the heat capacity and thermal conductivity of the fluid itself. A simpler way of detecting flow is to measure the increase in power required to maintain the temperature of a heated resistor at a constant value in the presence of fluid flow. This is the principle on which hot wire anemometer work and the power, P, dissipated in the wire is related to the flow velocity, v, as

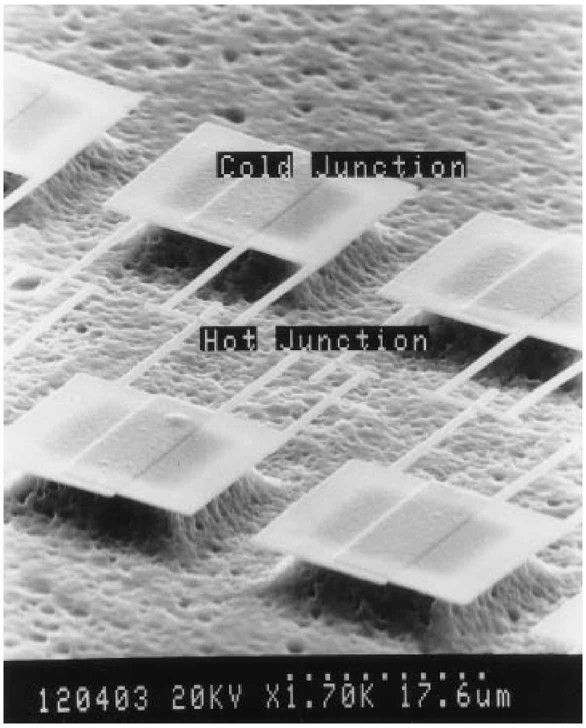

Figure 10. SEM micrograph of a copper-constantan free-standing microthermopile. The free-standing wires are 1 μm wide and the length of the free-standing wires is 35 μm. The cold junctions (large pads) are thermally attached to the substrate. The small thermal mass of the sensing element results in a fast response time of ~20 μs.

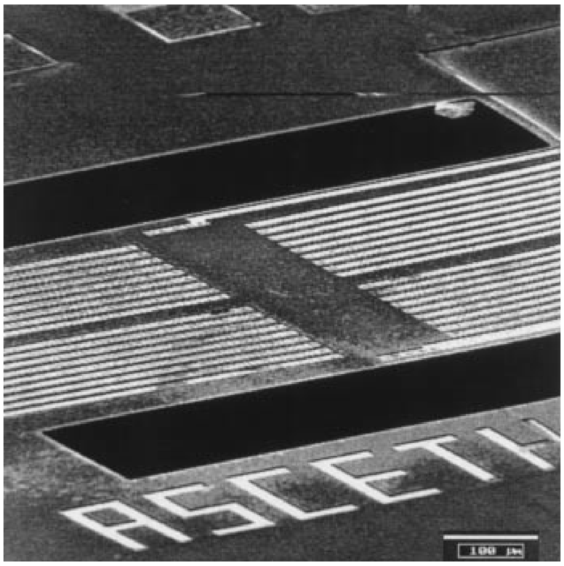

Figure 11. SEM picture of a bridge type flow sensor fabricated using bipolar technology. An n-doped monocrystalline silicon/aluminum thermopile with 36 thermocouples is located on both sides of a 1 mm by 0.5 mm bridge with a diffused heating resistor in the center of the bridge. (Courtesy Physical Electronics Laboratory, ETH, Zurich, Ref. 23)

$$P/\Delta T \propto v^{1/2} \tag{19}$$

where ΔT is the temperature difference between the wire and the fluid. Figure 11 shows a CMOS thermopile based flow sensor.

Thermal conductance of a gas is a function of the gas pressure (i.e., the dissipation of thermal energy from a heater to a heat sink across a small gap filled with the gas depends on the gas pressure). For a constant power dissipation in the heater, this pressure-dependent thermal conductance of the gas causes a variation in the heater temperature and provides an accurate way of measuring the gas pressure. The temperature of the resistor heater is measured using an integrated silicon-based thermopile. For the typical micromachined sensor geometries, these pressure sensors are best suited for vacuum measurements in the range of 10 mPa to 10 kPa. Such integrated thermopile-based vacuum sensors have been fabricated using both bulk and surface micromachining techniques, see Refs. (6) and (25).

A silicon accelerometer is based on the detection of movement of a suspended mass under the influence of acceleration. A thermopile based accelerometer detects the change in heat flow between the suspended mass and a heat source under the influence of acceleration. A typical sensor consists of a thermally isolated bridge with thermopiles on top of a heat source and a proof mass etched out of bulk silicon suspended in close proximity over the bridge (26).

Thermal Converters and Thermal Conductivity Sensors

In a thermal converter, electric power is dissipated into an ohmic resistor and converted into thermal power which is then measured using a thermopile-based temperature sensor. The operation of these sensors is based on the square-law relationship between the voltage and power. These devices have been used in wide-frequency-band ac power measurements and in particular for the measurement of microwave ac power (true root mean square voltage value) (6,25). In addition to ac power measurements, integrated thermopiles have also been used for the measurement of thermal conductivity of thin films and materials. Such sensors are based on the fabrication of micromachined freestanding structures of appropriate geometries in which the contribution to thermal effects of specific layers can be effectively isolated and quantified. These freestanding structures are heated by dissipating known quantities of electrical power and integrated thermopiles are used for the accurate temperature measurement in such structures (6,25).

Integrated Thermopile-Based Calorimeters

In microcalorimetry applications, the measurement junction of a thermopile is placed on a thermally isolated bridge or membrane structure and is coated with a catalytic layer for the desired chemical reaction. Under the influence of the surface catalyst, the chemical reaction takes place on the membrane surface and the heat of the reaction is detected by the change in temperature of the measurement junction of the thermopile with respect to the reference junction (27). This is an example of a chemical sensor based on microcalorimetry. If instead of a catalyst, a coating that converts absorbed microwaves into heat is used, the microcalorimeter can be used as a microwave sensor. Another example would be to coat the thermally isolated structure with a ferromagnetic coating with high hysteresis. Ac magnetic fields would cause heat generation in such a sensor structure, which can be measured using an integrated thermopile (8).

Thermoelectric Refrigeration

The passage of an electric current through a thermoelectric circuit can be used to cool one of its junctions by selectively pumping away heat to the other junction using Peltier effect. Since thermoelectric refrigerators contain no moving parts, they operate quietly, require very low maintenance and have a long life. In addition, the coefficient of performance of thermoelectric refrigerators is independent of the size of the system to be cooled which makes them ideally suited for low capacity cooling applications. However, the widespread use of thermoelectric refrigerators has been hindered by the higher costs and lower cooling efficiency as compared with the more commonly used compression-cycle refrigerators. Consequently, thermoelectric refrigerators are employed in certain niche application such as in spacecraft, artificial satellites, scientific equipment, cooled stages for laboratory applications where compactness, quiet performance, operation in vacuum environments, and high reliability are of major concern. Small cooling systems with powers of less than 10 W are commonly used as cold traps in vacuum systems, cooled stages inside vacuum chambers, as cooling jackets for cooled infrared detectors, as active heat sinks for cooling of main processor chips in personal computers, and for controlling the temperature of thermocouple reference junctions. Reviews on thermoelectric refrigeration can be found in Rowe and Bhandari (4) and Ioffe (28).

A thermoelectric refrigerator module is normally constructed such that all the cold junctions of the thermopile are on one face and the hot junctions on another face. Heat is pumped to the hot junction at a rate proportional to the cur-

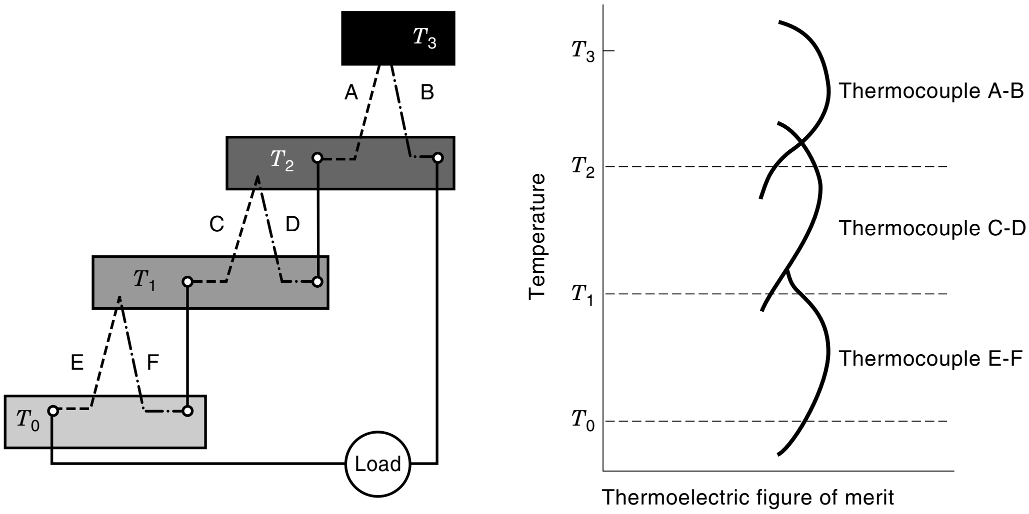

Figure 12. Schematic diagram illustrating the use of different thermocouples in a temperature sandwich arrangement. Each thermocouple operates at the best average Z value and the overall figure of merit is given by the envelope as shown on the right hand side.

rent in the circuit and to the number of thermocouples, N, constituting the thermopile. The most widely used materials in the construction of thermoelectric refrigerators are alloys of bismuth, antimony, selenium, and tellurium. Single layer module sizes range from 2.5 mm to 50 mm square and from 2.5 mm to 7.5 mm thick, with cooling capacities ranging from a few watts to about 100 W. The maximum temperature difference that a single thermoelectric module can produce for a coding power, $P_c = 0$ W, is around 65°C.

Thermoelectric materials have a different value for the thermoelectric figure of merit, Z, at different temperatures. If several thermocouple pairs are connected in series in a cascade arrangement at different temperatures as shown in Fig. 12, such that each thermopile operates at its best Z value, the overall coefficient of performance of the refrigerator can increased. Since the lower stages remove heat dissipated by the stages above them and from the load, multistage modules are constructed in a pyramidal shape as shown in Fig. 13. Multistage modules of up to six layers can generate several hundreds of watts of cooling capability and provide temperatures as low as -100°C with the heat sink at 27°C. In most small refrigeration systems with cooling powers in the range of up to 50 W, the pumped heat is dissipated into the surroundings by natural air convection or by using cooling liquids. In general, thermoelectric refrigeration systems are most economical cooling solutions for small cooling powers up to 50 W. In the 50 W and above cooling power range, thermoelectric systems are often more expensive and always less efficient than compression cycle systems. For these cooling powers, a thermoelectric system is only used if some other characteristic is of greater importance. Review of industrial thermoelectric cooling applications are presented in Refs. (29) and (30).

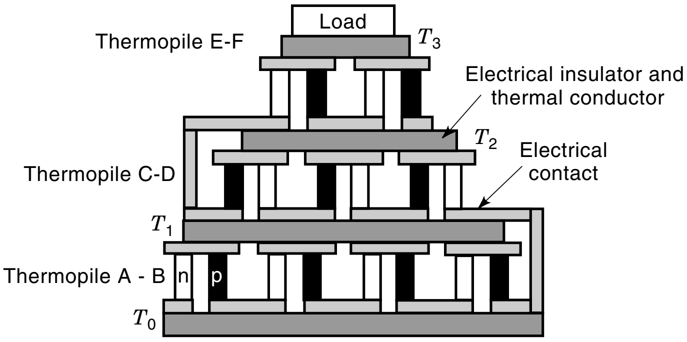

Figure 13. A three-stage schematic of the cascade arrangement of thermopiles. This arrangement affords flexibility in the geometrical requirements of each stage for optimal performance.

Thermoelectric Generators

Thermopiles can also be employed to generate electrical power if a temperature difference is maintained across its two faces. These thermoelectric generators are primarily used as remote, maintenance free, unattended power supplies in space stations and space vehicles, unmanned light houses, navigational buoys, remote mines, and drilling platforms. Another area where thermoelectric generators find application is in medical applications, especially as miniature batteries delivering under 300 μW of energy in cardiac pacemakers and other stimulator applications (4).

The main components of a thermoelectric generator are: (1) a heat source, (2) a thermopile, (3) a heat sink, and (4) an output control system. Most often, the physical arrangement of a thermopile generator is determined by the nature of its heat source. Thermoelectric generators are normally classified by the kind of fuel source they use as isotopic or nonisotopic. Nonisotopic generators are mainly powered by fossil fuels and to a limited extent by solar radiation. In isotopic generators, radioactive materials are used as the fuel sources. Radioactive isotopes emit high energy density over long periods of time. For example, plutonium (P-238) has a half life of 87 years and so the thermal output from the fuel capsule only decreases by 4% in 10 years. Thus, radioactive sources are very attractive fuel sources for thermoelectric generators. Currently all radioactive thermoelectric generators (RTGs) use either plutonium-238 or strontium-90 as the fuels (4,5). Depending on the kind of radiation emitted by each of these sources, elaborate care has to be taken to shield and confine the emission while maintaining the compactness and light weight of the entire system. In general, plutonium-238 requires minimal shielding and is best suited for space and medical applications where cost considerations are not important, while strontium-90 at one fortieth the cost of plutonium is employed in terrestrial applications where bulkiness of shielding is not an issue. However, due to safety and security reasons, RTGs have not been used for medical applications since the late 1980s. On the positive side, though, the development of these generators has had a significant impact on the development of high Z thin film materials.

Aside from the heat source, production of power using thermoelectric generators apparently seems very straightforward. The practical implementation, however, involves a very complex arrangement of coupling the heat source to the thermopile junctions while electrically isolating the junctions at the hot face of the generator module at the high operating temperatures. In addition, problems associated with material degradation and poisoning when continuously operated at high temperatures reduce the conversion efficiencies and performance over time. In general, the overall conversion of a thermoelectric device depends upon the temperature of its operation and the proportion of available heat which passes through the thermoelements.

Conventionally, thermoelectric power is generated at relatively high values of current and low voltage, with the load voltage from the thermoelectric module being about half the open circuit voltage of the thermopile. Solar powered thermoelectric generators using selective absorber coatings and with thermoelements fabricated from fine grained Si–Ge alloys have been predicted to operate with an efficiency of better than 12% between room temperature and 1000 K. A portable flame-powered generator, weighing about 5 kg, using leaded petrol as fuel, has been developed with a power output of 45 W at 6 Vdc and an overall efficiency of 2%. On the other hand, batteries powered by plutonium-238 and a bismuth-telluride thermopile module can supply several tenths of a volt for more than 10 years.

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