

2. The Thermopile

Radiometry is the science of measuring thermal radiation. The atoms and molecules that compose real materials are in motion, and the interactions among them (collisions and bonding forces) produce displacements in the elementary charges within them. The resulting accelerating charges and changing electrical dipole moments produce thermal radiation. The electromagnetic spectrum is depicted in Figure 2.1.

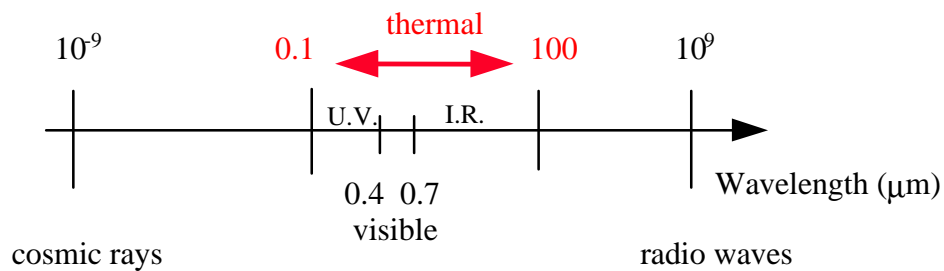


Figure 2.1. Electromagnetic spectrum

Based on the thermoelectric effect, the thermopile can be used as a heat sensor to measure thermal radiation. A thermopile is made of thermocouple junction pairs connected electrically in series. The absorption of thermal radiation by one of the thermocouple junctions, called the active junction, increases its temperature. The differential temperature between the active junction and a reference junction kept at a fixed temperature produces an electromotive force directly proportional to the differential temperature created. This effect is called a thermoelectric effect.

This chapter presents the background in thermoelectricity essential to understand the operation of a thermopile. It also presents the thermodynamics of the three effects in thermoelectricity: the Seebeck effect, the Peltier effect and the Thomson effect. The thermodynamics of thermoelectricity provides a means for describing the observed thermoelectric properties.

2.1 Background and Theory

Some concepts of thermoelectricity and solid-state physics are presented below so that the reader may better understand thermopile technology based on thermoelectric effects.

2.1.1 The thermoelectric effects

Any phenomenon involving an interconversion of heat and electrical energy may be termed a thermoelectric effect. We differentiate between reversible and irreversible energy conversion [Jaumont, 1960]. The best known irreversible thermoelectric effect is the Joule effect, where an electric current I (A) is transformed irreversibly into heat P (W) according to

$$P = R I^2, \quad (2.1)$$

where R (Ω) is the electrical resistance of the conductor.

The Seebeck, Peltier and Thomson effects are three related reversible thermoelectric effects. The thermocouple is well known and has been used extensively over the last 100 years for measurement of temperature and process control. The principle governing the operation of thermocouple devices is the Seebeck effect.

In 1821, Thomas Johann Seebeck (1770-1831), a German scientist, discovered that a small electric current will flow in a closed circuit composed of two dissimilar metallic conductors when their junctions are kept at different temperatures. A thermocouple consists of two such dissimilar metals connected in series. The electromotive force, or emf (V), that appears in an open circuit is the emf developed by the thermocouple to block the flow of electric current. If the circuit is opened the emf created, E_{AB} , is called the relative Seebeck emf (RSE), or Seebeck voltage. The emf E_{AB} (V) created is directly proportional to the differential temperature ΔT (K) between the two junctions

$$E_{AB} = S_{AB} \Delta T \quad , \quad (2.2)$$

where S_{AB} (V/K) is called the Seebeck coefficient.

This effect and is illustrated in Figure 2.2. The pair A-B of conductors, or thermoelements, creates the circuit which forms the thermocouple. The thermoelement A is the positive conductor with respect to B if the current flows from A to B in the cold junction.

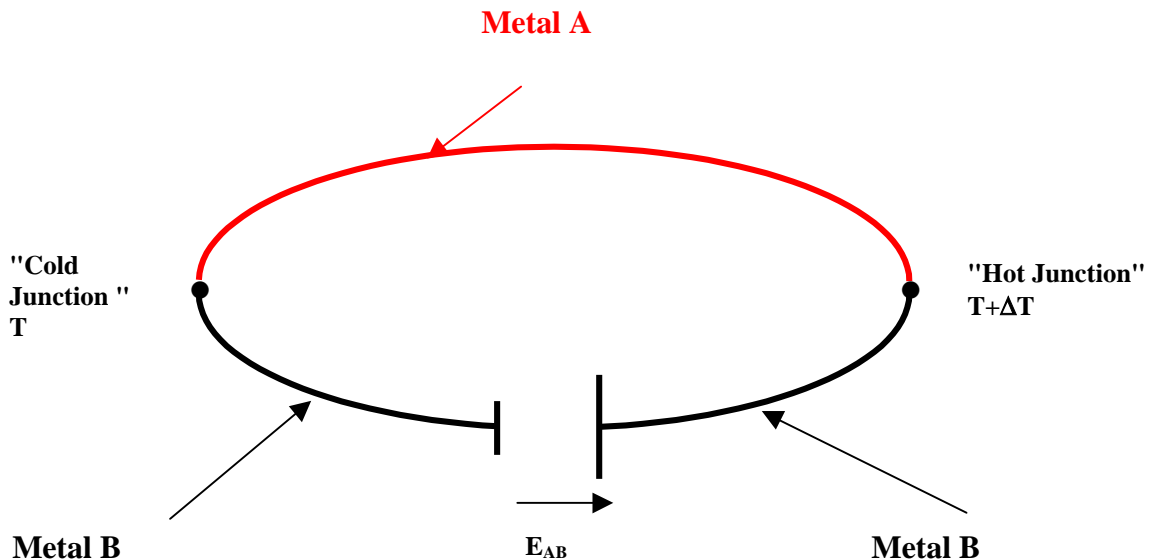


Figure 2.2. Illustration of the Seebeck effect.

In 1834, Jean Charles Athanase Peltier (1785-1845), a French watchmaker-turned-physicist, discovered that when an electric current flows across a junction of two dissimilar metals, heat is liberated or absorbed depending on the direction of this electric current compared to the Seebeck current. The rate of heat liberated or absorbed P (W) is proportional to the electric current I (A) flowing in the conductor, that is

$$P = P_{AB}(T) I, \quad (2.3)$$

where P_{AB} (V) is called the relative Peltier coefficient. This effect is the basis of thermoelectric refrigeration or heating. The Peltier effect is illustrated in Figure 2.3.

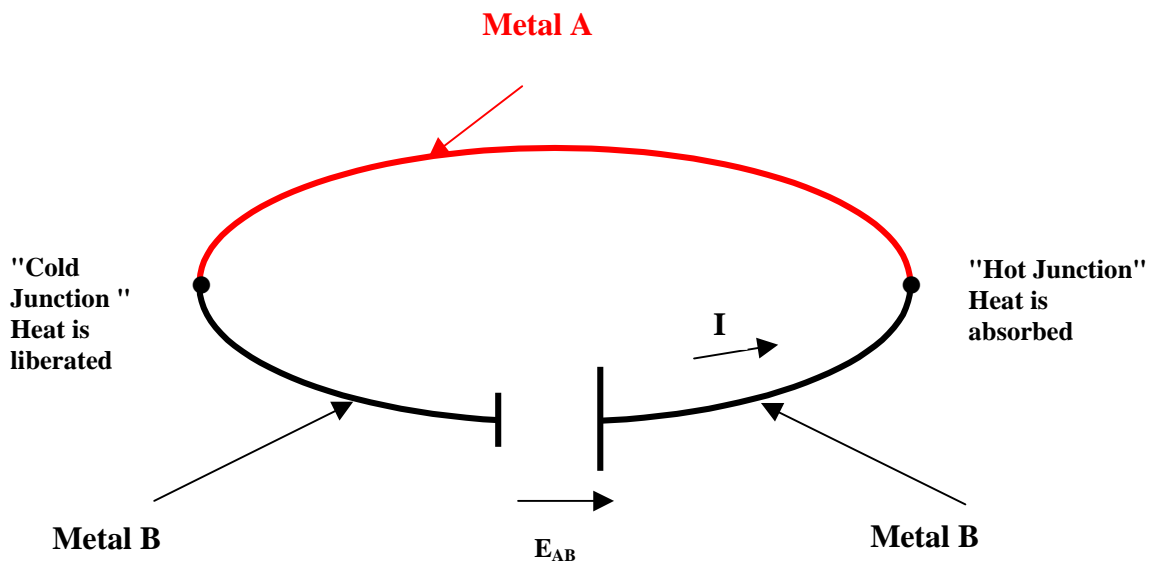


Figure 2.3. Illustration of the Peltier effect.

In 1852, Thomson discovered that if an electric current flows along a single conductor while a temperature gradient exists in the conductor, an energy interaction takes place in which power is either absorbed or rejected, depending on the relative direction of the current and gradient. More specifically heat is liberated if an electric current flows in the same direction as the heat flows; otherwise it is absorbed. Figure 2.4 illustrates the Thomson effect.

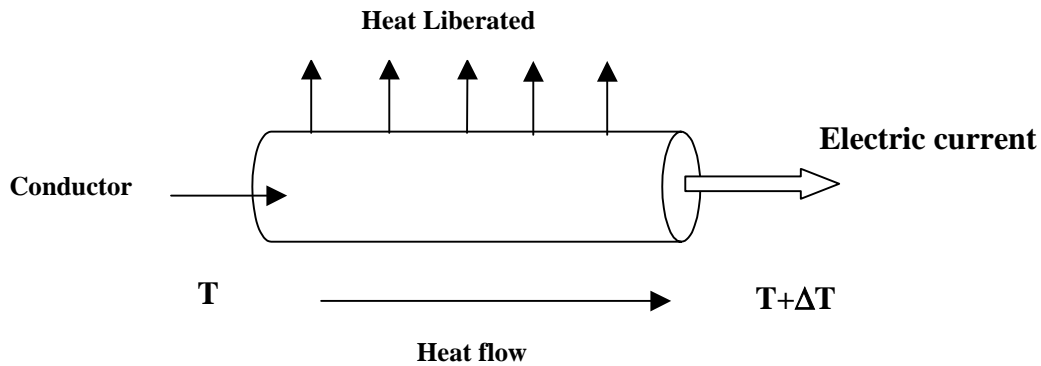


Figure 2.4. Thomson effect.

The power P' absorbed or rejected per unit length (W/m) is proportional to the product of the electric current I (A) and the temperature gradient $\frac{dT}{dx}$ (K/m), that is

$$P' = \sigma(T) I \frac{dT}{dx}, \quad (2.4)$$

where $\sigma(T)$ (V/K) is the Thomson coefficient.

While practical applications of the Thomson effect are few, the Seebeck effect is widely used in thermocouples to measure temperature and the Peltier effect is occasionally used for air conditioning and refrigeration units. Power generation is possible but because of the low thermal efficiency of the Peltier effect its commercial exploitation is of limited interest. Commercial exploitation of the Peltier effect has generally been limited to areas where quick heat and refrigeration is needed and where efficiency is not of utmost importance.

2.1.2 Thermodynamics of thermoelectricity

An understanding of the thermodynamic interdependency among the three reversible thermoelectric effects is critical. The thermodynamic theories presented here are essentially from the work of Pollock [1971].

Let us consider a thermoelectric circuit where Joule heating is neglected. This system can then be considered a reversible heat engine. Consider the circuit in Figure 2.1, where the cold junction is maintained at temperature T and the hotter junction at temperature $T+\Delta T$ by heat sinks and sources [Pollock, 1971]. If the emf generated in this circuit is E_{AB} (V), the thermoelectric power is defined as the change in emf per degree Kelvin, dE_{AB}/dT (V/K), such that the electrical voltage is given by

$$E_{AB} = (dE_{AB}/dT) \Delta T. \quad (2.5)$$

It should be noted that although dE_{AB}/dT is called the thermoelectric *power* its dimensions are not power (W) but volts per kelvin (V/K).

Taking into account the heat absorbed and liberated at the junctions (Peltier effects) and the heat absorbed and liberated within the conductors (Thomson effects), the conservation of energy in the system, considered as a reversible heat engine, in which a current I (A) flows, can be written as

$$(dE_{AB}/dT) \Delta T I = P_{AB}(T+\Delta T) I - P_{AB}(T) I + (\sigma_B - \sigma_A) \Delta T I, \quad (2.6)$$

where $P_{AB}(T+\Delta T) I$ (W) is the heat absorbed at the hot junction, $P_{AB}(T) I$ (W) is the heat liberated at the cold junction, $\sigma_B \Delta T I$ (W) is the heat absorbed in conductor B, and $\sigma_A \Delta T I$ (W) the heat liberated in conductor A.

If we simplify Equation 2.6 by dividing through by I and ΔT and then taking the limit as ΔT approaches zero, we obtain the fundamental theorem of thermoelectricity,

$$\begin{aligned} dE_{AB}/dT &= (dP_{AB}/dT) + (\sigma_B - \sigma_A). \quad (2.7) \\ \text{(V/K)} &\quad \text{(V/K)} \quad \text{(V/K)} \end{aligned}$$

This equation, which is homogeneous in V/K, gives the electrical Seebeck effect as the sum of the thermal Peltier and Thomson effects. This proves the relationship between the three effects

and is the basis of the statement that the **Seebeck effect is the result of both the Peltier and Thomson effects** [Pollock, 1985].

Let us now use the assumption that the thermoelectric interactions are thermodynamically reversible, and add heat sinks at temperature $T+\Delta T/2$ at the midpoints of the two conductors. The net change of entropy (kJ/K), of the heat sinks at the junctions and along the conductors is zero so for a unit time we can write

$$\begin{aligned} \frac{-P_{AB}(T+\Delta T) I}{T+\Delta T} + \frac{P_{AB}(T) I}{T} - \frac{\sigma_B \Delta T I}{T+(\Delta T/2)} + \frac{\sigma_A \Delta T I}{T+(\Delta T/2)} = 0 \end{aligned} \quad (2.8)$$

(kJ/K) (kJ/K) (kJ/K) (kJ/K)

After dividing through by the current I , if we multiply the first two terms by $\Delta T/\Delta T$ and then take the limit as ΔT approaches zero, Equation 2.8 becomes

$$-\frac{d}{dT} \left(\frac{P_{AB}}{T} \right) \Delta T - \frac{\sigma_B \Delta T}{T+(\Delta T/2)} + \frac{\sigma_A \Delta T}{T+(\Delta T/2)} = 0 \quad . \quad (2.9)$$

If we now define the Thomson effect as the energy change for a temperature difference of 1 K, that is $\Delta T = 1$ K, then since T generally is much greater than 1 K, we can assume that $T+\Delta T/2$ is essentially equal to T . We then have from Equation 2.9

$$\frac{d}{dT} \left(\frac{P_{AB}}{T} \right) = \frac{\sigma_A}{T} - \frac{\sigma_B}{T} \quad (2.10)$$

Carrying out the indicated differentiation in Equation 2.10 and multiplying each term of the resulting equation by T , we obtain

$$\frac{P_{AB}}{T} = \left(\frac{dP_{AB}}{dT} \right) + \sigma_B - \sigma_A \quad , \quad (2.11)$$

which gives the change in entropy per unit charge of the junction at a given temperature and relates the Peltier and Thomson effects.

Equation 2.11 can be simplified using the theorem of thermoelectricity, Equation 2.7 yielding

$$P_{AB} = \left(\frac{dE_{AB}}{dT} \right) T \quad , \quad (2.12)$$

where the Peltier coefficient, $P_{AB}(V)$, is described with respect to the thermoelectric power, dE_{AB}/dT (V/K).

If we differentiate Equation 2.12 with respect to T , we obtain

$$\frac{dP_{AB}}{dT} = \frac{dE_{AB}}{dT} + T \frac{d^2E_{AB}}{dT^2}, \quad (2.13)$$

and if we substitute this result into the theorem of thermoelectricity, Equation 2.7, Equation 2.13 becomes

$$\frac{d^2E_{AB}}{dT^2} = \frac{\sigma_A - \sigma_B}{T}. \quad (2.14)$$

Upon integration Equation 2.14 becomes, for closed thermoelectric circuits,

$$\frac{dE_{AB}}{dT} = \oint \frac{\sigma_A - \sigma_B}{T} dT = \oint \frac{\sigma_A}{T} dT - \oint \frac{\sigma_B}{T} dT. \quad (2.15)$$

Equation 2.15 shows that the thermoelectric power of a thermocouple can be expressed in terms of the Thomson coefficients of its components. In other words, the thermoelectric power is the algebraic sum of the absolute thermoelectric powers of its components:

$$\frac{dE_{AB}}{dT} = S_A - S_B = S_{AB}, \quad (2.16)$$

where $S_A = \int_0^T \frac{\sigma_A}{T} dT$ (V/K), and $S_B = \int_0^T \frac{\sigma_B}{T} dT$ (V/K), are the absolute Seebeck coefficients (ASC) of each of the components of the thermocouple materials, or thermoelements, A and B. The symbol S denotes the rate of change with temperature of the Thomson voltage in a single conductor.

The concept of the ASC is very important because it allows the study of the properties of individual thermoelements. If the ASC of one thermoelement is known and the thermoelectric power of the couple is determined experimentally, the ASC of the unknown element can be calculated using Equation 2.15.

After a second integration over a closed thermoelectric circuit, Equation 2.16 becomes

$$E_{AB} = \oint S_A dT - \oint S_B dT = \oint S_{AB} dT, \quad (2.17)$$

where the integrals of the Seebeck coefficients are the absolute Seebeck effects. The flow of current in this circuit is induced by the relative Seebeck coefficient (RSE) which is a consequence of the temperature difference between the two junctions of conductors A and B. Because the Thomson effect is present only when a current passes along the conductor, the Thomson coefficients (σ_A , σ_B) are nonzero only in closed circuits. This means that Equation 2.15 can account for thermoelectric properties only in a closed circuit. In contrast to this, the electrical potential (emf) within conductors is always present as long as a temperature difference is maintained between the two junctions, regardless of whether the circuit is open or closed. Hence Equations 2.16 and 2.17 are valid for both open and closed circuits. Usually the RSE is measured in open circuits to eliminate the Thomson and Peltier effects, which cause extraneous thermal variations.

From Equation 2.15 the three laws of thermoelectric circuits may be inferred:

- (1) the law of homogeneous conductors,
- (2) the law of intermediate conductors, and
- (3) the law of successive temperatures.

The law of homogeneous conductors states that a thermoelectric current cannot be maintained solely by application of heat to a single homogeneous conductor, regardless of any cross-sectional variations. In other words, if a thermoelectric circuit is formed of two conductors of the same homogeneous material ($S_A = S_B$), no emf exists in this circuit (Equation 2.16).

The law of intermediate conductors states that the sum of the absolute Seebeck coefficients of dissimilar conductors is zero when no temperature difference exists between the junctions. In other words no extraneous emf will be produced in a circuit made of intermediate materials if no temperature differences exist between the two ends of the materials. This law demonstrates that the contribution of a common thermoelement C to a pair of thermoelements A and B vanishes if the junctions A-C and C-B are at the same temperature.

The law of successive temperatures states that the emf of a thermocouple composed of homogeneous conductors can be measured or expressed as the sum of its properties over successive intervals of temperature. Mathematically this may be stated

$$E_{AB} = \int_{T_0}^{T_1} (S_A - S_B) dT + \int_{T_1}^{T_2} (S_A - S_B) dT + \int_{T_2}^{T_3} (S_A - S_B) dT = \int_{T_0}^{T_3} (S_A - S_B) dT . \quad (2.18)$$

2.1.3 Literature on thermoelectric effects

Thermodynamics provides a means for describing the observed thermoelectric properties; however it does not provide a model which can explain the mechanisms responsible for their behavior. The required model follows from an understanding of the roles of electrons in thermoelectric behavior.

The relative Seebeck emf produced in a thermoelectric circuit (RSE) has no relationship with contact potential, or Volta effect [Jastrzebski, 1976; Bridgman, 1934]. Contact potential is measured by the difference in work functions when two different metals are brought sufficiently close so that electron transfer creates a common Fermi level in both metals. This does not require a temperature difference and for closed circuits the net voltage is zero.

The thermoelectric effects can be explained by solid state physics [Callaway, 1991]. Two different materials have different free electron densities while they are both at the same temperature. A temperature difference merely gives the free electrons more kinetic energy to move around. When two materials are joined the most energetic electrons from one material will migrate to the other material in order to establish a new equilibrium of the junctions and balance the charge difference. This move disturbs the individual equilibrium of each of the materials. The disturbance is caused by the migration of energetic free electrons which leaves exposed positive charges on one side of the junction and an excess of negative charges on the other side. This causes an electric field to be formed across the junctions. Since the temperature determines how energetic the free electrons will be and since their migration determines how many exposed positive and excess negative charges are on the two sides of the junction, it follows that the magnitude of the electric field is a function of temperature. In a closed circuit a Seebeck current forms from the electric field and circulates in the loop. At one junction where the electric field has the same direction as the generated current, the current flows easily; at the other junction where the electric field and the generated current have opposite directions, the current must travel against the electric field. This explains the Peltier effect: the junction where the Seebeck

current flows easily is the junction maintained at the higher temperature and thus the current absorbs heat in an effort to cool the junction to the equilibrium temperature. At the other junction the Seebeck current has to go against the electric field, thus having to do work heating up the junction in an effort to bring the temperature up to the equilibrium temperature.

It must also be pointed out that in most references [Bridgman, 1934; Pollock, 1993] emphasis is placed on the fact that the Seebeck effect is only dependent on the temperature difference between the two junctions made of dissimilar and homogeneous conductors. It does not depend on the junction cross-section, the temperature distribution (i.e the temperature gradient) inside those conductors. This hypothesis is known as the Magnus law. Isotropy and homogeneity of the metal forming the conductors is a requirement of this law. However, because there are stresses and strains in any solid metal in which there is a temperature gradient, the universal applicability of the law must be called into question. Even with the qualification that the metal be isotropic and free from stress, there is not unanimous acceptance of this law. Benedicks [1933] claimed the existence of other thermoelectric effects not generally taken into account. Among these thermoelectric effects is a "homogeneous thermoelectric effect," which is a temperature difference in the steady state between the ends of a long uniform wire carrying a steady current. These effects are generally considered to be sufficiently small to be neglected.

2.2 The Thermopile

This section is aimed at describing the thermoelectric sensor proposed for use as a thermal radiation detector. The motivation behind the choice of such a device is developed, as are detailed descriptions of its operation, specifications and expected performance.

2.2.1 Description of the device

Thermocouple operation is based on the Seebeck effect; thus, the amount of electrical potential produced can be interpolated as a measure of temperature difference. But what is the relationship is there between the emf produced in the open circuit and the temperature difference between the two junctions? It all depends on the pair of thermoelements used: some pairs of

thermocouple elements give a Seebeck voltage which varies in an anticipated way with temperature. Thermocouples in common use have nearly linear temperature-emf characteristics. Once the thermocouple calibration curve is obtained, by maintaining one of the junctions at a known fixed temperature, the other junction is used as the measuring junction and is held at the temperature to be determined. The junction maintained at a known temperature is called the reference junction while the other is called the active junction.

For an ideal thermocouple, the open-circuit voltage obtained is proportional to the temperature difference between the junctions constructed of conductors A and B,

$$\Delta V = S_{AB}(T) \Delta T, \quad (2.19)$$

where S_{AB} is the relative Seebeck coefficient, expressed in $\mu\text{V}/\text{K}$. This coefficient depends not only on the temperature, but also on the choice of the two materials used in the thermocouple. A sign is assigned to the Seebeck coefficient according to the sign of the potential difference related to the temperature difference. However, it is much more convenient to work with absolute values: the magnitude of the Seebeck coefficient of a junction is then calculated as the absolute value of the difference between the Seebeck coefficient of each metal; that is,

$$S_{AB} = |S_A - S_B|. \quad (2.20)$$

Because a voltage is produced when a temperature difference exists between the two junctions of the thermocouple junction pair shown in Figure 2.2, the thermocouple can be used as a detector of incident radiation. In open-circuit operation the emf produced is usually low, on the order of a tenth of a microvolt per degree celsius of temperature difference for a single junction pair. In order to increase the output voltage, several junction pairs may be connected in series. The responsivity is then increased by n if n thermocouple junction pairs are placed in series; that is,

$$\Delta V = nS(T) \Delta T. \quad (2.21)$$

Such a device is called a thermopile. As shown in Figure 2.5, based on the description by Dereniak [1984], elements of a series of thermocouples of alternate material A and B are placed between a heat source and a heat sink. The hot junction comes into thermal equilibrium with the high temperature surroundings producing an emf at the leads. If a current flow results, thermal

energy is converted into electrical energy. The remaining energy absorbed at the hot junction is rejected to the heat sink at the cold junction.

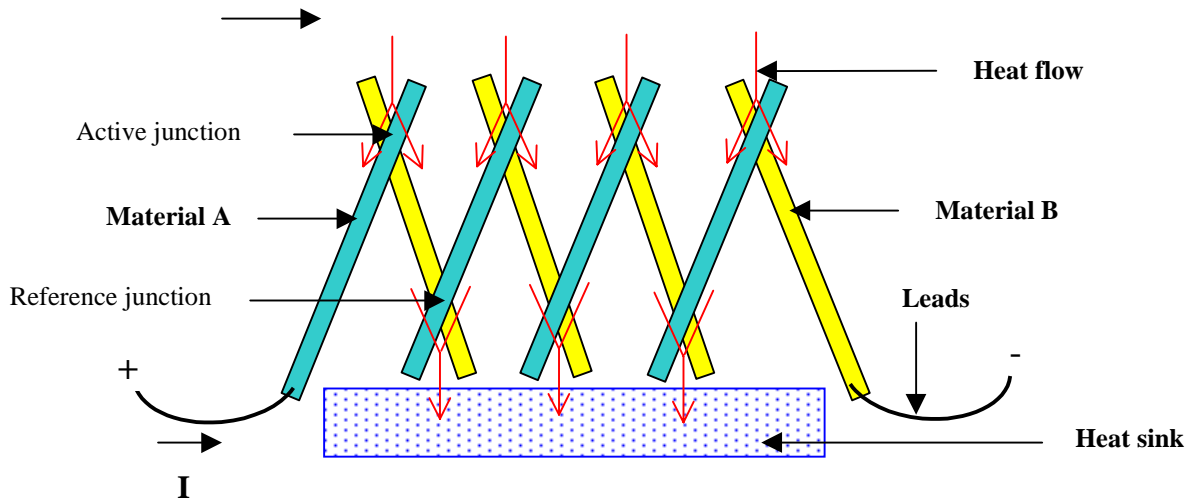


Figure 2.5. Example of a Thermopile

We now turn our attention to thermal radiation detectors. The two most important parts of all thermal radiation detectors are the absorber and the temperature transducer. When a thermopile is used, the radiant energy is absorbed into a layer coated on the active junction which acts as the heat source, and the difference of temperature between the active and the reference junctions is translated into an output voltage through the Seebeck effect. In most practical implementations we can neglect the Joule, Thomson and Peltier effects because the input impedance of the signal-conditioning circuit is sufficiently high to ensure that a negligible current flows through the thermopile.

2.2.2 Motivation for the choice of a thermoelectric device

The main goal of this research is to develop a thermal radiation detector capable of measuring small radiation heat fluxes (on the order of 1 W/m^2) arriving from the Earth when the device is in a high Earth orbit. One of our first motivations for replacing the current CERES bolometer sensors with thermopiles is to achieve higher sensitivity. The new thermoelectric sensor, whether for the GERB program (linear array of thermocouple sensors) or for future CERES-like missions (more likely to be a linear array of thermopiles), must be capable of accurate heat flux measurements.

The use of a thermopile in this application offers many advantages over the bolometer. First, bolometers need a matched pair of thermistors in adjacent arms of a two-active-arm bridge circuit. If the instrument temperature changes, both the active and compensating sensors will be affected in the same way and the bridge will deflect in a known way. Measuring the output voltage by adding an external circuit has many drawbacks. First, it is not easy to manufacture two thermistors with exactly the same physical properties and dimensions. It is also difficult to estimate the self-heating effect in the thermistors, which must carry a current in order for their resistances to be measured. In the case of the thermopile a compensating element is not needed. The thermopile generates its own emf and therefore does not need a bias power supply as does the thermistor bridge circuit. Thus, no self-heating or other thermoelectric effects are present. In addition, the thermopile has the advantage of measuring temperature differences directly without any offset: if no radiation hits the detector, the output voltage signal is zero [Dereniak, 1984]. The thermopile also provides a potentially fast time response.

Furthermore, progress is currently being made at Vatec, Inc., in the field of microsensor element manufacturing. Vatec has a unique ability to exploit this latest technology. Vatec's current thermopile manufacturing process uses sputtering technology, which consists of a vacuum chamber where an inert gas is introduced and ionized. The ions are accelerated by an electric field and directed onto a metal target. Metal ions are liberated by the kinetic energy exchange with the gaseous ions and eventually condense into a film on the desired surface. The total thickness of the sensor elements laid down on the surfaces with this process is less than $2 \mu\text{m}$. Thus, the resulting sensor has a small volume and therefore a minimum heat capacity and

therefore a fast time response. The current thermopiles sold by Vatel have time responses of 5 to 10 μ s. Once the thin-film layers have been deposited on the substrate they are laser sliced into pixels, with each pixel yielding a thermocouple junction pair. Actually, this process allows thousands of nearly identical microsensors to be manufactured in one run, on a micrometer size scale. The sensitivity of the thermopile and its performance-to-cost ratio are in this way improved. Figure 2.6 shows the fabrication sequence for the thermopile linear-array thermal radiation detector.

The semiconductor sensor technology field is also moving at a rapid pace [Sze, 1994], and is still under intensive study. The use of semiconductor materials provides a far better Seebeck coefficient which, according to Equation 2.20, directly increases the sensitivity of the device. The current detector concept is unique because it uses thermocouple junctions made of platinum and an amorphous semiconductor of zinc and antimony (50 percent Zn-50 percent Sb). This combination can give values of the Seebeck coefficient as high as 900 mV/K according to Krieder [1994]. In other words it increases the Seebeck coefficient by a factor of several hundred over traditional metal-metal junctions.

With these encouraging prospects, the goal to develop a detector with high sensitivity, a low electrical resistance, a fast time response and in a repeatable way appears achievable.

2.2.3 The thermopile thermal model

If, at a certain level of complexity, we consider the one-junction-pair thermopile as a lumped system, the heat exchanges with the external environment are the heat input, that is the radiant energy incident to the detector (at T), and the heat losses through conduction to the heat sink and radiation to the surroundings (at T_a). If we assume that the temperature of the absorbing layer of the thermopile is near the ambient temperature, the heat loss through radiation can be neglected. Figure 2.7 shows the energy balance for the system.



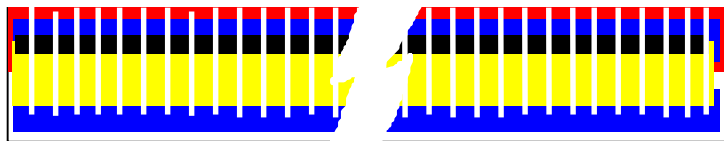
Step 1. Parylene thermal insulation (red) deposited on aluminum nitride substrate (white).



Step 2. Platinum (blue) busses are sputtered onto parylene and aluminum nitride.



Step 3. Zinc-antimonide (yellow) is sputtered to form junctions with the two platinum busses.



Step 4. Active junction is coated with an absorber layer (black) and then laser sliced into pixels.

Figure 2.6. Fabrication sequence for the thermopile linear array [Mahan, 1997]

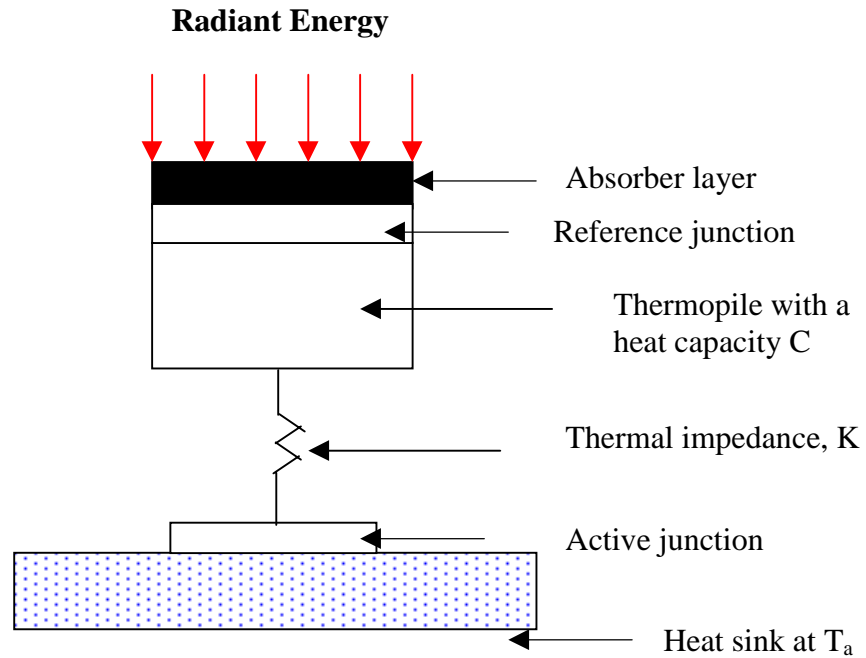


Figure 2.7. The energy balance on a system consisting of a thermal mass, C , and a thermal impedance of conductance K .

For this specific system the energy balance leads to

$$C \frac{d\Delta T}{dt} + K \Delta T = P_e \quad . \quad (2.22)$$

In Equation 2.22 P_e is the radiant energy absorbed in the absorber layer (W), K the thermal conductance (W/K) between the thermopile and the heat sink, and C the heat capacity of the thermopile (J/K),

$$C = m C_p \quad , \quad (2.23)$$

where m is the mass (kg) and C_p is the specific heat (J/kg.K) of the thermopile, and the thermal conductance, K , is defined by

$$K = \frac{A k}{L} \quad , \quad (2.24)$$

where L is the length (m), A is the cross-sectional area (m^2) and k the conductivity of the material (W/m K).

If the rate of absorbing radiant energy is constant, the solution to Equation 2.22 is

$$\Delta T = \frac{P_e}{K} \left(1 - e^{-\frac{K}{C}t} \right) , \quad (2.25)$$

so the thermal radiation detector behaves like a first-order system with a thermal time constant of

$$\tau = \frac{C}{K} . \quad (2.26)$$

Therefore Equation 2.25 can be written

$$\Delta T = \frac{P_e}{K} \left(1 - e^{-t/\tau} \right) . \quad (2.27)$$

The output voltage of a thermocouple can be computed by simply multiplying the temperature difference by the Seebeck coefficient, yielding

$$V = n S \Delta T = n S \frac{P_e}{K} \left(1 - e^{-t/\tau} \right) . \quad (2.28)$$

The sensitivity of the instrument is defined as the output voltage divided by the input power and has the units of V/W/m², that is

$$\text{Sensitivity} = \frac{V}{P_e} = \frac{n S}{K} \left(1 - e^{-t/\tau} \right) . \quad (2.29)$$

In order to minimize the time response, a system needs a high thermal conductance K and a small heat capacitance C , whereas to maximize the sensitivity, given by Equation 2.29, a system needs a small thermal conductance K , a large Seebeck coefficient S and a sufficient number of thermocouple pairs n . This suggests that the thermal conductance K between the thermopile and the heat sink has to be optimized in order to meet the requirements of both high sensitivity and fast time response. Thus, the function of the parylene thermal resistance layer is critical since the value of the thermal capacitance K depends mainly on its thermal conductivity and dimensions.

2.2.4 The thermoelectric radiation detector specifications and design

The proposed sensor consists of a linear array of thermocouple junction pairs. Each thermocouple junction pair is made of platinum and zinc-antimonide with an active junction laid down on a thermal resistance layer made of parylene to insulate it from an aluminum-nitride heat sink. A detailed profile of one thermocouple junction pair showing the materials and layer thicknesses appears in Figure 2.8.

The primary function of the parylene thermal resistance layer is to increase the device sensitivity. However, we have seen that it also influences the time response. An absorber layer is added on top of the device to absorb the incident radiation. The spectral absorptivity of the absorber determines the device spectral response, since the temperature change produced at the thermopile junctions is directly related to the amount of power absorbed by the absorber layer. For that reason the absorber must be chosen with care to give as spectrally flat a response as possible. This is what motivates our choice of the same absorber material as that used on the bolometer of the CERES instruments [Priestley, 1997]. This absorber material is made of black Chemglaze z-306 paint with 10 percent additional carbon to maximize its absorptance.

Table 2.1 shows the nominal material and the thermal properties of the thermopile, the absorber layer and the heat sink.

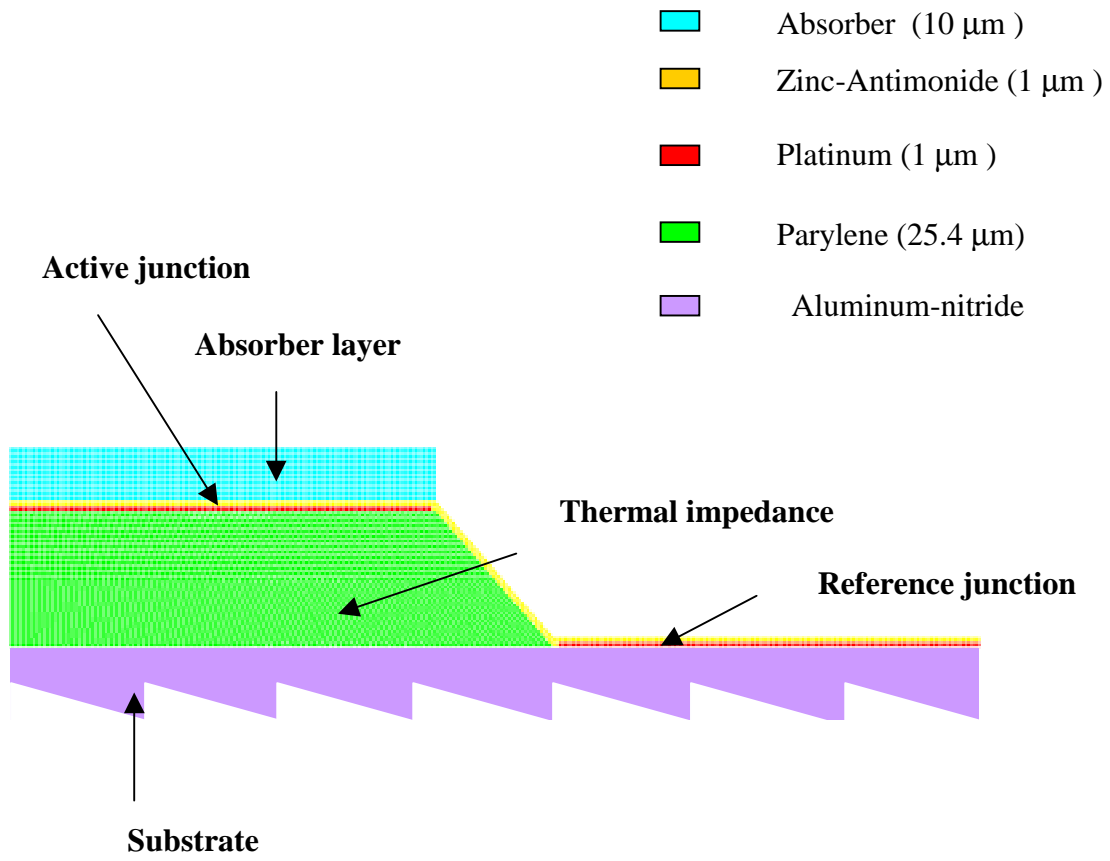


Figure 2.8. Profile of the thermocouple design.

Table 2.1. Nominal material and thermal properties of the thermopile, the absorber layer and the heat sink.

	Mass density (kg/m ³)	Specific heat (J/kgK)	Conductivity (W/mK)	Electrical resistivity (Ω m)
Platinum arm	21450	133	71.6	$10.6 \cdot 10^{-8}$
Zinc Antimonide arm	6880	200	60	$12.5 \cdot 10^{-4}$
Aluminum nitride heat sink	3260	800	165	10^9
pyrlene thermal resistance	1289	712	0.084	$8.8 \cdot 10^{14}$
absorber layer (Chemglaze)	1400	669	0.209	-

The expected performance of the thermopiles is a high sensitivity ($> 0.27 \mu\text{V/W/m}^2$), a fast time response ($< 20 \text{ ms}$), and a low electrical resistance ($< 30 \text{ k}\Omega$).

2.2.5 Parameters available to improve the sensitivity of the device

The dimensions, the conductivity, and the geometry of the parylene resistance layer are parameters available for improving the sensitivity of the device. This implies the need for a compromise between the time response and sensitivity. A thicker resistance layer gives a better sensitivity but the time response is then degraded because of added thermal mass and resistance. Additionally, the absorber has to be sufficiently thick to absorb the irradiant power and at the

same time sufficiently thin not to influence the time constant. Also, up to a point, the spectral response is likely to be flatter if the absorber layer is thicker. A compromise must also be found between the sensitivity and time response.

To summarize, the parameters which could be used to improve the thermopile design are:

1. the thermal resistance layer material and its geometry,
2. the dimension of the gap between the active and the reference junctions, and
3. the thickness of the absorber layer.

The next chapter is dedicated to describing the finite element model created to study the time response and sensitivity of the thermopiles. More details are given about the parameters used to achieve an optimized design.