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A. PREPARATION

1. Phenomenological Overview

In the first half of the nineteenth century, two rather amazing electrical phenomena were discovered which demonstrated that a flow of current could have thermal consequences quite apart from ohmic heating of the conductor.

The first of these was discovered in the middle 1820's by Thomas Johann Seebeck (1770-1831), a German physician. He found that, when two dissimilar conductors are combined into a closed circuit and the junctions maintained at different temperatures, a current will flow. Alternatively, if the circuit is opened well away from the junction, an electromotive force can be observed; this is, of course, the basis of the thermocouple and is illustrated in Fig. 1. The important notion here is that the emf displayed by the voltmeter will be nonzero if and only if $\Delta T$ is nonzero: in the absence of meltdowns and the like, $T_0$, $T_L$, and $T_V$ are immaterial. Moreover (law of Magnus) the effect is independent of the way in which temperature is distributed between the two junctions.

The second effect was discovered about 1834 by Jean Charles Athanase Peltier (1785-1845), a French watchmaker of independent means. What he observed was that, if an electric current is passed through a junction between two conductors, then heat will be absorbed or evolved at the junction at a rate which depends upon the magnitude of the current and with a sign which depends upon the direction of the current. This is illustrated in Fig. 2. The passage of the current $I$ causes heat to be transferred between the reservoirs 1 and 2 which are, insofar as possible, thermally isolated from each other: the direction of heat transfer depends upon the direction of the current.

In considering the Seebeck and Peltier effects, William Thomson (1824-1907; a.k.a, Lord Kelvin) concluded that there must be a thermodynamical relation between them for which he derived an erroneous relationship (cf. MacDonald, 1962). Since his relationship was at variance with experimental reality, he postulated the existence (along a length of homogeneous wire) of a heat production which was (i) reversible, (ii) linear in the temperature gradient along the wire, and (iii) linear in the current. Mirabile dictu such a Thomson heat turned out to exist, can actually be measured against the background of Joule (i.e., ohmic) heating, and is related simply to the Seebeck and Peltier effects by

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References for this section are Bridgeman (1934), Heikes and Ure (1961), and Rowe and Bhandari (1983).
NOTATION:

- Junctions between conductors
- Conductors actively used in thermocouple
- $\mathcal{X}$: A "test" conductor
- $\mathcal{R}$: A "reference" conductor (Frequently lead when $\mathcal{X}$ is an unfamiliar substance.)
- A lead (Usually copper.)
- An isothermal region
- $T$: Temperature. $T_0$ is the temperature of a "reference" junction, $T_0 + \Delta T$ that of a "test" junction, $T_L$ that of the laboratory, and $T_V$ that of the voltmeter.

Figure 1
Thermoelectricity

NOTATION:

- Junctions between conductors
- Conductors actively used in thermocouple
- $X$: A "test" conductor
- $R$: A "reference" conductor (Frequently lead when $X$ is an unfamiliar substance.)
- A lead (Usually copper.)
- An isothermal region.
- $Q$: The heat content of an isothermal region.
- $T$: Temperature. $T_1$ and $T_2$ are temperatures of two thermoelectrically active junctions, $T_L$ that of the laboratory, and $T_I$ that of the current generator.
- $T_1 = T_2$ does not imply $Q_1 = Q_2$ and vice versa.
- $I$: A loop current.

Figure 2

what are now known as the Kelvin relations.

Although these notes will discuss all three effects, the laboratory will emphasize the Peltier effect.
2. **Empirical Foundations**

To quantify the Seebeck effect, consider the circuit of Fig. 3A. The sense of the voltage $E_{AB}$ is commonly taken to be positive if the sense of the current flow (the two $B$ leads having been shorted together) is from $A$ to $B$ at junction 1; that is, the circulation of positive current is clockwise around the loop. Experiment then shows that, if $C$ be a third conductor and $T_3$ a third temperature,

$$E_{AB}(T_1, T_2) = E_{AC}(T_1, T_2) - E_{BC}(T_1, T_2)$$

(1)

and

$$E_{AB}(T_1, T_3) = E_{AB}(T_1, T_2) - E_{AB}(T_3, T_2)$$

(2)

These two properties combine to imply the existence for any conductor $X$ of an absolute thermal electromotive force $E_X(T)$ such that (cf. Bardeen, 1958)

$$E_{AB}(T_1, T_2) = [E_A(T_1) - E_A(T_2)] - [E_B(T_1) - E_B(T_2)]$$

$$= [E_A(T_1) - E_B(T_1)] - [E_A(T_2) - E_B(T_2)]$$

(3)

However, these relations do not uniquely define $E_X(T)$ since an arbitrary function $\phi(T)$ can be added to the several $E_X(T)$ without affecting Eqs. (1)-(3). One could arbitrarily choose $E_{AR}(T) = 0$ for some arbitrary reference material $R$, setting $E_{AR}(T) = E_A(T)$; and this is often done in tables. Or one could simply tabulate values of $E_{AB}(T_1, 273.15)$ for a variety of common combinations; and this also is often done. Fortunately, as will be seen later, $E_{R}(T)$ can be determined absolutely without direct Seebeck measurements. For measurements at and below room temperature, $R$ is taken to be lead (Pb) for which very accurate measurements exist (Roberts, 1977); lead unfortunately melts at 327.50ºC, and there is as yet no commonly agreed upon standard for high temperature work.

Note well that the Seebeck effect is *NOT* a contact phenomenon: rather, it is a phenomenon that requires contact. The effect is a function of the two bulk conductors that enter the isothermal contact regions; but it is indifferent to the nature of the contact itself. Nevertheless, Eq. (3) does indeed have the form of a difference between two potentials that are associated with junctional regions.

To quantify the Peltier effect, consider the setup of Fig. 3B. If a quantity of heat $\Delta Q$ [J] is abstracted from the isothermal region about the junction when charge $\Delta q$ [C] passes from $A$ to $B$, then the Peltier coefficient [J/C]

$$\Pi_{AB}(T) = \lim_{\Delta q \to 0} \frac{\Delta Q}{\Delta q} = \frac{dQ}{dq}$$

(4)

---

2 An excellent reference for this is Bardeen (1958).
By the convention outlined above, \( \Pi_{AB}(T) > 0 \) when the passage of positive charge from \( A \) to \( B \) cools the junction. The Peltier effect, like the Seebeck effect, reflects the difference of the intrinsic Peltier coefficients of the two bulk materials \( A \) to \( B \) and therefore

\[
\Pi_{AB}(T) = \Pi_A(T) - \Pi_B(T). \tag{5}
\]

To quantify the Thomson effect, consider the length of wire of material \( X \) shown in Fig. 3C. Let a carrier of charge \( q \) pass through the hatched region and in the process remove an amount of heat \( \Delta Q \). Then the Thomson coefficient \([\text{V/K}]\) is given by

\[
\frac{1}{q} \lim_{x \to 0} \frac{\Delta Q}{\Delta T} = \frac{1}{q} \frac{dQ}{dT} = \mu_X(T). \tag{6}
\]

By convention, \( \Delta Q \) is reckoned positive for cooling, and \( \mu_X(T) > 0 \) when a flow of positive charge in the direction of increasing temperature results in such cooling. Surprisingly, despite the existence of Joule heating, it is possible accurately to measure \( \mu_X(T) \) (Blatt, Schroeder, Foiles, and Greig, 1976; Roberts, 1977).

Picturesque and conceptually useful interpretations of the three effects will now be given: the reader is cautioned not to take them too seriously. First, \( E_{AB}(T) = [E_A(T) - E_B(T)] \) may be thought of as a junctional potential somewhat homologous to the liquid junction potential of electrochemistry: a unit positive charge going from \( B \) to \( A \) acquires energy \( eE_{AB}(T) \). Second, the Peltier coefficients are in some sense latent heats of evaporation of the charge carriers; hence, a unit positive charge going from \( B \) to \( A \) takes up energy \( e \Pi_B(T) \) vaporizing from \( B \) and gets back energy \( e \Pi_A(T) \) condensing in \( A \), for a net energy gain \( e[\Pi_{AB}(T)] \). Third, \( \mu_X(T) \) may be considered as a sort of specific heat of a charge carrier which, in going from \( T_1 \) to \( T_2 \), must alter its "internal energy" by \( e \int_{T_1}^{T_2} \mu_X(T) dT \).
Thermoelectricity

Figure 3

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3. Simple Theory
   
   a. Thermodynamic

   Consider now a unit positive charge $\Theta (=1.602 \ldots \times 10^{-19}$ C) passing clockwise and infinitely slowly around the adiabatic network of Fig. 4. Consider next a small population of positive charges which circulate clockwise once around the closed loop, taking in all a time $\tau$ [s] and giving rise to a current $i(t)$. If energy is to be conserved and the system is to be adiabatic, the electrical work done on the charge carriers, less the joulean loss, plus the thermal energy acquired by these carriers must be zero:

   \[
   0 = \left[ E_R(T_1) - E_X(T_1) \right] \int_0^\tau i(t) \, dt + \left[ E_R(T_2) - E_X(T_2) \right] \int_0^\tau i(t) \, dt + \\
   \left[ \Pi_R(T_1) - \Pi_X(T_1) \right] \int_0^\tau i(t) \, dt + \left[ \Pi_R(T_2) - \Pi_X(T_2) \right] \int_0^\tau i(t) \, dt - \\
   \left[ \int \mu_R(T')dT' + \int \mu_X(T')dT' \right] \int_0^\tau i(t) \, dt - R \int_0^\tau i^2(t) \, dt,
   \]

   where $R \Omega$ is the total resistance around the loop. Now let material $R$ be a reference with respect to which coefficients are measured and assume that the $X$ coefficients tend to 0 as $T_2 \to 0$. Then, with $T_1 = T$ and $T_2 = 0$,

   \[
   0 = E_X(T) + \Pi_X(T) + \int \mu_X(T')dT' + R \int_0^\tau i^2(t) \, dt / \int_0^\tau i(t) \, dt
   \]

   This is well covered in the monograph edited by Heikes and Ure (1961). The reader is, however, cautioned that there is nothing simple about the signs of the various coefficients and that careful perusal of the several references will all most certainly lead to abysmal confusion.

   Thermoelectricity – 8
Next let our hypothetical current \( i(t) = I \), a constant; and take the limit \( I \to 0 \).

\[
0 = E_X(T) + \Pi_X(T) + \int_0^T \mu_X(T')dT'.
\] (9)

Eq. (9) is commonly known as the First Kelvin Relation and is simply an expression of the first law of thermodynamics.

A second equation relating the coefficients can be demonstrated heuristically (if not rigorously) by noting that, as \( i(t) \to 0 \), only reversible processes are involved in Eq. (8). Thus the thermoelectric consequences of moving a small charge around the circuit must follow from the theory of adiabatic reversible processes and be isentropic. This says that a summation (over each portion of the circuit) of the ratio (heat acquired by moving charge)/\( T \) will yield zero. That is,

\[
0 = \left[ \Pi_R(T_1) - \Pi_X(T_1) \right] \frac{1}{T_1} + \left[ \Pi_X(T_2) - \Pi_R(T_2) \right] \frac{1}{T_2} - \left[ \int_{T_1}^{T_2} \mu_R(T') \frac{dT'}{T'} + \int_{T_1}^{T_2} \mu_X(T') \frac{dT'}{T'} \right].
\] (10)

And this reduces to

\[
\Pi_X(T) + T \int_0^T \mu_X(T') \frac{dT'}{T'} = 0,
\] (11)

the Second Kelvin Relation and a consequence of the second law of thermodynamics\(^4\).

Eqs. (9) and (11) taken together imply

\[
E_X(T) = T \int_0^T \mu_X(T') \frac{dT'}{T'} - \int_0^T \mu_X(T')dT'.
\] (12)

Hence, if \( \mu_X \), the Thomson coefficient of \( X \), is known as a function of temperature, then \( \pi_X \) and \( E_X \), Seebeck and Peltier coefficients, can be found by a simple integration. More importantly, each is related to the other two.

Finally, it is useful to define a quantity \( S_X \) [V/K], called the Thermopower.

\[^4\text{It may be pointed out (Epstein, 1937) that the third law of thermodynamics implies both} \ \Pi_X/T \to 0 \text{ and} \ \mu_X \to 0 \text{ in the limit} \ \ T \to 0.\]
\[
S_x(T) = \int_{0}^{T} \mu_x(T') \frac{dT'}{T}.
\] (13)

In practice, this quantity is quite useful. For example,
\[
\Pi_x(T) = -TS_x(T),
\] (14)
\[
\frac{dE_x}{dT} = S_x(T),
\] (15)
\ [
\Pi_x(T) = -T\frac{dE_x}{dT}.
\] (16)

b. Physical

The fundamental processes that underlie thermoelectric phenomena are, in their details, beyond the scope of this course. Nevertheless, they can at least be indicated in a hand-waving fashion. A simple, idealized solid conductor can be thought of as a gas of highly mobile charge carriers sloshing about in a regular lattice of fixed charges. Energy transport, as by standard heat conduction or a thermoelectric effect, is not necessarily confined to either the fixed or the mobile charges. Energy transfer by the fixed charge carriers can be accomplished by lattice vibrations known as phonons and gives rise to the so-called "Phonon-Drag-Thermopower." The transfer by free charge is more obviously electrodiffusive in nature and gives rise to what is termed the "Diffusion Thermopower".

Comparisons of theory with experiment (e.g., Blatt et al., 1976; Roberts, 1977) have revealed that, over intermediate temperature ranges (say 50-250 K), the functional forms of temperature dependence of \(S\) can be qualitatively accounted for, at least for noble or alkali metals. If one (a) desires the size or even the sign of the dependence, (b) becomes curious about high temperature behavior, or (c) wants to work with polyvalent metals, alloys, or semiconductors, the theory is much less satisfying. That is, present day theoretical understanding of the thermoelectric coefficients is good enough to yield the broad outlines of experimental reality, but has yet to enable the design and commercial production of thermoelectric devices capable of fulfilling the seductive promise thermoelectricity. A recent review of the situation has been given by Rowe (1995).
4. *Theory of Device Efficiency*\(^5\)

A practical thermoelectric device will most probably be used for either the direct generation of electric power, or refrigeration\(^6\), or the measurement of temperature. In temperature measurement, efficiency is relatively unimportant. And, in both power generation and refrigeration, device efficiency turns out to depend upon a figure of merit universally dubbed \(Z\). This section will show how \(Z\) \([\text{K}^{-1}]\) arises in power generation.

Consider the simple circuit of Fig. 5. Let it be assumed that \(T_0\) is fixed and that \(\Delta T\) can vary.

![Diagram of thermoelectric device](image)

**Figure 5**

The device efficiency will then be given by

\[
\eta = \frac{P_L}{H},
\]

where \(P_L\) [W] is the joulean power developed in the load resistance \(R_L\) [\(\Omega\)] and \(H\) [W] is the power which must be added at the hot junction to maintain its temperature. It is known experimentally (Or can be inferred by Taylor expansion!) that

\[
E(T_0+\Delta T, T_0) = \beta \Delta T + \sum_{n=2}^{\infty} \frac{\beta_n(\mathcal{A}, B;T_0)(\Delta T)^n}{n!} \to \beta \Delta T.
\]

In effect, we assume that \(E\) is independent of temperature. Thus the current which will flow is

\[
I = \frac{\text{thermoelectric voltage}}{\text{total resistance}} = \frac{\beta \Delta T}{R_L + R_\mathcal{A} + R_B},
\]

where the electrical resistance of an arbitrary lead is naturally \(R = L/(A\sigma)\), \(L\) being lead length, \(A\) lead cross-sectional area, and \(\sigma\) the electrical conductivity of the material. Hence,

\[
P_L = \frac{(\beta \Delta T)^2}{R_L(1+\epsilon)^2},
\]

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\(^5\) This discussion follows that of Chapter I of Heikes and Ure (1961). More detailed discussions are to be found in Chapters 11 and 15 of Heikes and Ure (1961) and in the monograph by Harman and Honig (1967). The somewhat more recent compilation by Rowe (1995) can also be usefully consulted.
where
\[ \varepsilon = \frac{R_A + R_B}{R_L}. \]  

(20b)

To evaluate \( H \), reflect that it must admit to splitting into four parts as
\[ H = H_P - H_J + H_C + H_T, \]  

(21)

where \( H_P \) is the rate of heat transport from the hot junction by the Peltier effect; \( H_J \) is the rate at which joule heat in the leads returns to the hot junction; \( H_C \) is the rate of heat transport from the hot junction to cold junction due to standard thermal conduction; and \( H_T \) is the heat carried off by Thomson processes.

First,
\[ H_P = \Pi_{A_B} |I| > 0, \]  

(22)

where the sign of \( I \) has been adjusted to preserve the inequality and thereby represent head absorption. This represents entirely standard Peltier cooling.

Second, simple one-dimensional heat flow theory shows that one-half of the joulean heat generated in each conductor flows back to the hot junction\(^7\). Thus
\[ H_J = I^2 R_L \varepsilon. \]  

(23)

Third, if the leads \( A \) and \( B \) are presumed to be well insulated to suppress lateral loss,
\[ H_C = \Delta T \left( \kappa_A \frac{A_A}{L_A} + \kappa_B \frac{A_B}{L_B} \right) > 0, \]  

(24)

where \( \kappa \) [W/(m·K)] is the thermal conductivity of a lead.

Fourth, and finally, there will be no Thomson heat transfer since, by Eqs. (13), (15), and (18),
\[ \mu_X(T) = T \frac{d^2 E_X}{dT^2} = (T_0 + \Delta T) \frac{d^2 E_X}{d(\Delta T)^2} = 0. \]  

(25)

Hence
\[ H_T = 0. \]  

(26)

What this means is that the equation for the efficiency \( \eta \) is very complex indeed; but that the geometrical and material parameters (lead length and area, \( \beta, \sigma, \kappa \)) can perhaps be tweaked to optimize efficiency. What such an exercise normally reveals is that
\[ \eta_{\text{max}} \propto \frac{\Delta T}{T} f(ZT), \]  

(27)

where \( T = T_0 + \frac{1}{2} \Delta T \) and the figure of merit \( Z \) is

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\(^6\) It can, of course, also be used for heating. But, in practice, it never would be unless heating and cooling applications alternated: pure heating is rather more simply accomplished by straight joulean dissipation.

\(^7\) The “A” student will of course feel an overwhelming compulsion to demonstrate that this is indeed the case.
\[ Z = \frac{\beta^2}{\sqrt{\kappa_A/\sigma_A} + \sqrt{\kappa_B/\sigma_B}}. \] 

(28)

With increasing \( ZT \), \( f(ZT) \) slowly approaches unity from below, and \( ZT \) should exceed five if this limit is to be at all closely approached. Obviously, as \( ZT \to 0 \), \( f(ZT) \) should also.

The goal of the device physicist has long been to find materials with elevated Seebeck coefficient \( \beta \) whose individual members had low \( \kappa/\sigma \) ratios. This has proven not to be an easy task (cf. Rowe, 1995). First, the thermal conductivity has two components: An “electronic” component (though holes also matter) which is linearly proportional to the electrical conductivity; and a lattice component carried by vibrations of the background structure through which the charge carriers move. Totally squelching the lattice component can drop the \( \kappa/\sigma \) ratios only so far. After that, boosting \( Z \) depends upon tweaking \( \beta \) which in turn affects \( \sigma \).

5. **Philosophical Interlude (What Went Wrong?)**

The utility of thermoelectric phenomena for the measurement of temperature or for critical cooling tasks where efficiency is of secondary importance is well established (cf. Rowe, 1995). What has long been deemed, however, to be of greater practical significance is to make commercial scale power generation or refrigeration feasible: Unfortunately, this demands much greater efficiencies than currently can be achieved.

By the 1950s, people had begun to experience a belief that modern semiconductor science was mature enough to enable them to keep \( \sigma \) low while shrinking \( \kappa \) and thereby to boost \( Z \) to levels at which device efficiencies were respectable\(^9\). With a little prodding from the Navy's Bureau of Ships, a massive attempt at technological breakthrough blossomed; and by 1960 there were several hundred workers engaged in seeking that breakthrough. The net result of a decade of work was disillusionment, for the dreams of the many workers (including the great Clarence Zener) never came to pass. True, modest increases in efficiency were achieved, but \( Z \) never reliably reached levels in the realm above \( 5 \times 10^{-3} \). Worse yet, \( Z \)'s high enough to be deemed marginal were generally associated with substances having catastrophically poor material properties of some other sort\(^10\). As one engineer put it: "As a class, they have the most exasperating mechanical properties of any materials I've encountered... you

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\(^8\) This section owes much to a most illuminating article by Charles J. Lynch (1972). A more up to date overview is provided by Nolas and Slack (2001).

\(^9\) The basic idea was to find a good material and then make one leg of the couple n-type and the other p-type.

\(^10\) The legendary gadolinium selenide (\( Z \sim 45 \times 10^{-3} \)) showed a tendency to melt during tests. Germanium telluride was too brittle to work with and too difficult to make electrical contact to.
can't heat them up, you can't make contact to them, you can't solder them without destroying the thermoelectric performance. They are a constant threat to a man's sanity."

Will $ZT$ ever be pushed into the useful range beyond 5 in a couple with useful mechanical properties? Perhaps, yes. Perhaps, no. There is no clear theoretical reason why it cannot. But then the scientist's ability to accurately predict materials of a desired thermoelectric coefficient leaves something to be desired. What is known is that, in the fifties and sixties of the last century, nothing much came of a very substantial effort in which virtually every obvious possibility was tried\footnote{As one disappointed individual put it: "When you get down to the lower right hand corner of the periodic table and you still haven't found what you are looking for, you have to face the idea that you have run out of things to play with."}. And it is also known that a renewed effort in the past decade has pushed the thermal lattice conductivity quite close to its theoretical minimum without getting the desired values for $ZT$ (Nolas and Slack, 2001). If a breakthrough is to be had, it will have to come from the serendipitous recognition of a non-obvious semiconductor compound; or it will have to await a goodly amount of growth in our practical understanding of complicated semiconductors\footnote{See also the comments by Heikes and Ure (1961, ch. 11).}

6. **Present Day Practicalities**

Where the typical engineer is apt to meet thermoelectricity, other than in a thermocouple, is in a thermoelectric temperature controller. For these devices, there are fairly simple design rules. Let a coefficient of performance [dimensionless] be defined as (Heikes and Ure, 1961, ch. 15).

$$\phi = \left| \frac{H_c}{P_e} \right| \leq \left| \frac{T_c}{\Delta T} \right|,$$

where $P_e$ [W] is the electric power supplied to the thermoelectric device, $H_c$ [W] is the flux of heat supplied to the controlled junction to maintain its equilibrium temperature despite the Peltier cooling, $T_c$ [K] is the temperature of the controlled junction, and $\Delta T$ [K] is the temperature difference between the controlled junction and a "reference" or "heat-sunk" junction at $T_r = T_c + \Delta T$. Normally the design is made for maximum cooling since, relatively, it is much easier to heat the junction. Also, it should be noted that the Carnot limit $T_c/\Delta T$ can greatly exceed unity.

Next, let $H_c$ be split into two parts as

$$H_c = H_d + H_s,$$

where $H_d$ [W] is the heat generated within the device being temperature regulated by the controlled junction and $H_s$ [W] is the flux of heat which seeps (leaks) into the controlled device from the exterior. One normally has but little control over $H_d$ but can drastically reduce $H_s$ with suitable insulation.
Further let the thermal impedance between the heat-sunk reference junction and ambient at \( T_0 \) [K] be \( R \) [K/W]. Clearly, at equilibrium,
\[
P_e + H_c = \frac{[T_r - T_0]}{R}. \tag{31}
\]
since ultimately the heat-sunk junction must dispose of all the thermal energy which appears in the temperature-controlled device. Since \( H_d \) and \( H_s \) are apt to be fairly well set by the envisaged application\(^{13}\), a worst case evaluation of \( [T_r - T_0] \) would permit the evaluation of minimum allowable thermal impedance of the heat sink if \( P_e \) were known. It is in the determination of \( P_e \) that the only design finesse is required.

A simplified method of determining \( P_e \) follows. It will yield, in most cases, entirely satisfactory results.

(i) Determine the \( T_c \) range required.

(ii) Estimate the maximum \( T_r - T_c = \Delta T \) to be encountered on cooling; heating in most (though not all) applications is trivial if the thermoelectric module is adequate for the envisaged cooling.

(iii) Go to a manufacturer's catalogue and pick out a unit which will do the job. The requisite data are \( H_c \), \( \Delta T \), and anticipated maximum \( T_r \). The catalogue most commonly will provide tables or curves of \( H_c(I) \) and \( \phi(I) \) with \( \Delta T \) and maximum \( T_r \) as parameters. A typical set of curves for the Cambion model 801-2003-01-00-00 is shown in Fig. 6; this is the module employed in our laboratory exercise\(^{14}\).

(iv) From the characteristic curves and \( H_c \) find \( I \). From \( I \) find \( \phi(I) \). From \( H_c \) and \( \phi \), find \( P_e \). Example: with \( H_c = 21 \text{ W} \), \( \Delta T = 16 \text{ K} \), \( T_r = 40^\circ \text{C} \), and \( T_0 = 25^\circ \text{C} \), it follows that \( I = 3.72 \text{ A} \), \( \phi = 1.040 \), \( P_e = H_c/\phi = 20.2 \text{ W} \), and \( R < 0.364 \text{ K/W} \). For higher efficiency one could of course choose to use \textit{two} (2) units each drawing 10.5 W and discover \( I = 1.92 \text{ A} \), \( \phi = 1.888 \) and \( P_e = 2 \times (10.5/1.888) = 11.1 \text{ W} \).

As a rough rule of thumb, one can distinguish two classes of cooling operation. In the first, we wish merely to keep \( T_r - \Delta T = T_c \) below some critical value and don't want to waste undue joules doing it; here one tries to operate near the peak of \( \phi \). In the second, refrigeration is merely an offshoot of control

\(^{13}\)Despite the fact that it may be preordained by the application, \( H_s \) may nevertheless be hard to estimate in advance.

\(^{14}\)Cambion is a long-vanished firm. And our thermoelectrical units are ancient. But they are in great shape and may well last forever. Take care that devices which you design are as trustworthy.

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and efficiency is less important than precision of control; here one gets a unit of impressive capability and lets the control circuitry regulate current and pumping rate.

7. References


Figure 6. Cambion Model 801-2003-01-00-00 Characteristics
B. **EXPERIMENT**

1. **Equipment List**

   1. Instrument rack with the standard gear
   2. Temperature probes
   1. Load box fixture to interconnect the DC wall outlet (+50 V, 0 V, ground) to the thermoelectric module
   1. Thermoelectric cooling module mounted on a heat sink, supplied with a cooling fan, and fused for 5 Amp
   1. Jar of ZnO thermal compound. This will aid you in making contact between the temperature probe and various surfaces. *Be neat and clean it up when you’re through!*
   1. FET switching module
   2. 2 rheostats
   1. Current Shunt

2. **Procedure**

   a. **General setup.** The first requisite is to make certain that you have the correct voltage available. To this end, plug the Load Box of the Power experiment into the DC wall outlet and connect the green binding post to system ground. Turn on the DC outlet and verify that Hi is about 50 VDC above LO and that LO is approximately at Mother Earth potential; then turn off the wall outlet. *IT IS THE RESPONSIBILITY OF THE STUDENT TO ASSURE THAT THE CORRECT VOLTAGES ARE IN FACT AVAILABLE.*

   Next, connect an ammeter and the two variable rheostats in series between the open terminals on the load box labeled WM/I so that there is continuously variable (0-100 Ω) resistor between them. Set the resistance to maximum. *THE USE OF TOO SMALL A CURRENT LIMITING RESISTANCE CAN FRY THE THERMOELECTRIC MODULE AND DEVASTATE YOUR GRADE.*
Now plug the thermoelectric module into the Load Box: red jack to HI and black jack to LO; be sure to include an appropriate ammeter in this circuit. Plug the fan cord into an ordinary 120 VAC outlet. The unit is now ready to cool.

However, before plunging into the experiment proper, take note of Part 2.e in which you are called upon to make unspecified additional measurements to prepare an equivalent circuit for the thermoelectric module.

b. **Maximum cooling.** Turn on the device power and adjust the rheostats to give 3.0 Amp device current. Check the cold face of the thermoelectric module at intervals until it has equilibrated thermally. In °C, measure $T_c$ (Cooling Device Temperature), $T_r$ (Heat Sink Reference Temperature), and $T_o$ (Room Ambient Temperature). Then place a foam insulating block over the cold face, wait 10 min, and repeat the temperature measurements; measure $T_c$ through a hole in the foam block. Remove the foam insulator. Turn off the power to the device.

c. **Minimum temperature versus current.** Set up the unit as a cooler without insulation. Determine equilibrium values of input voltage and device temperatures ($T_c$, $T_r$, and $T_o$) in °C over $I = [0.5 \ (0.5) \ 3.0]$ Amp. Turn off the power. Reverse the leads to reconfigure the unit as a heater. Repower and adjust the current to get $T_c = 60^\circ$C at thermal equilibrium; determine $T_r$, and $T_o$ and the requisite current. Turn off device power.

d. **Minimum temperature versus thermal mounting.** Reconfigure the unit as an uninsulated cooler. Unplug the fan, thereby slashing convective heat flow from the heat sink. Power up and set $I = 1.0$ A. Determine equilibrium $T_c$, $T_r$, and $T_o$. Turn off device power. Restart the fan.

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* How do you know it has reached equilibrium?
* Optional for extra debit: Forget to watch $T_c$ and cook the unit.
e. **Seebeck phenomena.** Here your principle aim is to measure $V_S(\Delta T)$, where $V_S$ is the Seebeck voltage and $\Delta T = T_r - T_c$. Therefore, reconnect your apparatus so that a Switching Module (Fig. 7) is in series *between* the load box and the thermoelectric module. Drive the Switching Module with a continuous train of pulses of maximum amplitude (at least $\pm 6V$) and suitable for actuating the module to yield a long ON cycle with a short OFF cycle; the desired pulse repetition rate (PRR) is 360 Hz. Use the HIGH output of the function generator. Prepare to detect the AC and DC currents through the thermoelectric module and the voltage waveform between the thermoelectric module high and low sides. **Make sure that the waveforms flat during the long ON cycle.** If it isn’t, increase the function generator output until it is. **Failure to do so will destroy the FET in the controlling circuitry.** Hopefully, at this stage of the course, such measurements should not be a problem. Next, turn on your measurement system and set the DC (average) current to 3.0 A; measure equilibrium values of $I_{AC}$, $I_{DC}$, $T_r$, $T_c$, $V_M$ (the transmodule voltage during the ON phase) and $V_S$ (the trans-module voltage during the OFF phase). Have the instructor verify that the correct waveform has been obtained. As a minimum, copy the scope display for the 3.0 A case. Repeat for 0.5 Amp spaced values of the DC current all the way down# to 0.5 Amp taking data as required.

f. **Clean-up.** **Before** presenting your data to the instructor to be signed, present your thermoelectric module and the two temperature probes from which you have thoroughly removed the white thermal compound&.

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# Are your instructors here delicately hinting at the advisability of an allometric analysis, or are they crudely messing with your minds?

& “thoroughly” will be judged by a handling test and by visual inspection: if the instructor’s hands get even a little white or if white mess can be seen, your effort will be rejected.
Figure 7 Switching Module
C. REPORT

a. Present a table of $T_C$, $T_r$, $T_0$, and $\Delta T$ for both the insulated and uninsulated 3.0 Amp cases from Part B.2.b. Comment briefly. Also, describe the rule of thumb by which you assured that thermal equilibrium had been reached.

b. Prepare a table of $I$, $V_M$, $T_C$, $T_r$, $T_0$, $(T_r-T_0)$, and $\Delta T$ from Part B.2.c. On the same graph, make plots of $\Delta T$ and $(T_r-T_0)$ versus DC current for cooling; be sure to specify $T_0$. On this graph also indicate $\Delta T$ and $(T_r-T_0)$ for the $T_C = 60^\circ C$ heating case. Comment cogently. Also, describe how you obtained the correct current for the heating case.

c. Describe and discuss the effects of inhibiting convection noted in Part B.2.d. Be laconic, but transfer the requisite quantitative information, qualitative information, and deep understanding.

d. Prepare a table showing $I_{DC}$, $I_{AC}$, $V_M$, $T_C$, $T_r$, $T_0$, $\Delta T$, and $V_S$ using data taken in Part B.2.e. Present a graph of $V_S$ versus $\Delta T$; from the data and deduce with detailed explanation the Seebeck coefficient. On another single graph sheet, present plots of $\Delta T$, $T_r$, and $I_{AC}$ versus $I_{DC}$. Discuss tersely. Include a copy of the scope display for the 3.0 A case.

e. Examine the circuit diagram for the Switching Module; and answer the following questions*

   (i) Why was the transformer coupling needed on the input? Could not the experiment have been designed to permit the pulse generator to drive the FET directly?

   (ii) Why was a pulsed waveform used? What’s wrong with a simple square wave?

f. Devise and justify an equivalent circuit for the thermoelectric module. Carefully support your model with experimental data, and provide numerical values for all model parameters.

* In semesters when a majority of students did not answer this question, it has been known to reappear on the Final. Therefore, think Thévenin and figure one out.