UNCLASSIFIED

AD NUMBER

ADB063461

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; 11 AUG 1981. Other requests shall be referred to School of Aerospace Medicine, Brooks AFB, TX 78234.

AUTHORITY

AFMC ltr 16 Aug 1996

THIS PAGE IS UNCLASSIFIED

Review 1-81

AEROMEDICAL REVIEW

THERMOELECTRIC COOLING: REVIEW AND APPLICATION

Edward S. Kolesar, Jr., Captain, USAF

December 1981

Distribution limited to U.S. Government agencies only; test and evaluation; 11 August 1981. Other requests for this document must be referred to AMD/RDO.

USAF SCHOOL OF AEROSPACE MEDICINE
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas 78235

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

NOTICES

This final report was submitted by personnel of the Crew Environments Branch, Crew Technology Division, USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, Brooks Air Force Base, Texas, under job order 2729-00-20.

This technical report has been reviewed and is approved for publication.

Edward S. Kolesar, Jr.
EDWARD S. KOLESAR, JR., Captain, USAF
Project Scientist

RICHARD L. MILLER, Ph.D.
Supervisor

ROY L. DEHART
Colonel, USAF, MC
Commander

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Aeromedical Review 1-81	2. GOVT ACCESSION NO.: AD-B063	3. RECIPIENT'S CATALOG NUMBER: 462L
4. TITLE (and Subtitle): THERMOELECTRIC COOLING: REVIEW AND APPLICATION		5. TYPE OF REPORT & PERIOD COVERED: Final Report, Dec 1980 - Feb 1981
		6. PERFORMING ORG. REPORT NUMBER: SAM-TR-81-26
7. AUTHOR(s): Edward S. Kolesar, Jr., Captain, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: USAF School of Aerospace Medicine (VNL), Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas 78235		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62202F, 2729-00-20
11. CONTROLLING OFFICE NAME AND ADDRESS: USAF School of Aerospace Medicine (VNL), Aerospace Medical Divison (AFSC), Brooks Air Force Base, Texas 78235		12. REPORT DATE: December 1981
		13. NUMBER OF PAGES: 79
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report): Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; test and evaluation; 11 August 1981. Other requests for this document must be referred to AMD/RDO.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Thermoelectric cooling; conventional electromechanical cooling; heat pump; thermoelectric materials; Seebeck effect; Peltier effect; Thomson effect; Fourier effect; Joule effect; maximum coefficient of performance; maximum heat pump capacity; heat transfer; human thermal burden; chemical warfare; thermoelectric figure of merit; and human thermal conditioning.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Presented here are the theory, the applications, and an analysis of the problem of cooling a ground troop dressed in chemical warfare protective clothing. The analysis models the human thermal burden, resulting from metabolic and environmental heat production. For the thermal burdens considered, the analysis shows that the current thermoelectric cooling technology will not practically or efficiently support total thermal reg lation. A discussion of marginal cooling is recommended as a possible option if thermoelectric cooling is to be pursued.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

CONTENTS

CONTENTS (Cont'd.)

Figures

Tables

THERMOELECTRIC COOLING:
REVIEW AND ANALYSIS

INTRODUCTION

Why consider thermoelectric cooling as a means of dissipating the heat generated by the environment and human metabolism for a ground troop dressed in chemical warfare (CW) protective clothing? This Review attempts to answer this question and also to explain some of the advantages and disadvantages associated with thermoelectric cooling technology.

COMPARISON OF COOLING TECHNOLOGIES

Since thermoelectric cooling systems (heat pumps) are often compared to conventional electromechanical cooling systems, one way to highlight the similarities and differences in these two refrigeration technologies is to describe the respective systems.

Conventional Electromechanical Cooling Technology

In a conventional electromechanical cooling system, mechanical work is performed on a fluid; and the result is a thermodynamic cycle (1-5). During part of the cycle, the temperature of the fluid is above the ambient sink temperature, and thus dissipates heat. During another portion of the cycle, the temperature of the fluid is below the temperature of the medium to be cooled, and thus absorbs heat. A conventional electromechanical cooling system (Fig. 1) has four fundamental components: a condenser, compressor, evaporator, and an expansion valve (1,2,5). As illustrated in Figure 1, beginning at point 1, the fluid is usually in the gaseous state (mixture of vapor and liquid droplets or mist). The compressor raises the pressure and temperature of the fluid. The compression must be sufficient to raise the temperature of the vapor (point 2) above that of the ambient sink. The condenser is a heat exchanger which cools the vapor by dissipating its superheat and latent heat of condensation to the ambient, and the result is a subcooled liquid (point 3). The expansion valve is a device to separate regions of high and low pressure. Expansion through the valve results in a drop in the fluid temperature below that of the source of heat (point 4). The evaporator is a heat exchanger which absorbs heat from the medium to be cooled, and thus raises the temperature of the fluid to point 1 (Fig. 1), from which the thermodynamic cycle originated.

EDITOR'S NOTE: Available at the close of this publication is a selective list (plus definitions) of the "Abbreviations, Acronyms, and Symbols" used throughout the Review.

Thermoelectric Heat Pump

In contrast to the conventional electromechanical cooling system, a thermoelectric heat pump is a solid-state device with no moving parts, fluids, or gases. The basis of this system (heat pump) is the thermoelectric element. As illustrated in Figure 2, a thermoelectric element consists of a series connection of two semiconductors, one of which possesses electron conductivity (n-type), and the other, hole conductivity (p-type) (6-46). With a suitable source of direct current input power, a thermoelectric element forms a hot and cold junction with the two semiconductor materials. At the cold junction, energy, in the form of heat, is absorbed by electrons as they pass from a low energy level to a higher energy level. At the hot junction, on the other hand, heat is liberated because the electrons return from the high energy level to the lower energy level (6,72).

Thermoelectric heat pumps were originally developed in the 1960's to satisfy unique and exacting military and aerospace temperature regulation applications (73-86). When these devices failed to compete economically with conventional electromechanical cooling technologies for mass applications (such as domestic refrigerators), most large companies, and industry in general, lost interest. Since then, these devices have found use primarily in special-purpose applications (7-10,11-13,16,21,22,24-27,29,30,33-35,38,40-42,54,56,58, 68,69,71,73-253) that include:

a. military/aerospace (cooling infrared, photomultiplier, and charge-coupled-device detectors);
b. laboratory/scientific (laser tuning, cooling electronic integrated circuits, cold chambers, microtome stage coolers, osmometers, and dew-point hygrometers);
c. medical (hypothermia blanket chillers, ophthalmological cornea freezers, blood analyzers, and tissue processing refrigerators); and
d. commercial (aircraft water coolers, mobile refrigerators, restaurant display case coolers).

Thermoelectric heat pumps, commercially available in various shapes and sizes, provide a means to cool objects, fluids, and gases to well below ambient temperatures. A typical thermoelectric module (fundamental building block) consists of 44 thermoelectric semiconductor elements; is 1.5 in. by 1.5 in. square, and 0.25 in. thick (3.81 cm by 3.81 cm square by 0.64 cm thick); and weighs approximately 25 grams (254-257).

In addition to being compact, lightweight, and insensitive to orientation, thermoelectric heat pumps offer very high reliability, good maintainability, low cost of operation, accurate and rapid thermal regulation, and a low operating noise level. The high reliability of thermoelectric heat pumps has been demonstrated by a number of operating systems which have performed for very long periods of time with no thermoelectric module failures or known degradations (113,122,143,145,149,150,159,179,217,233,234,236,246). The solid-state modular nature of the thermoelectric heat pump module permits rapid replacement of defective components and prompt reentry into service. In contrast to operators of conventional compressor refrigeration systems, service personnel do not require high skill levels (and thus need shorter training periods).

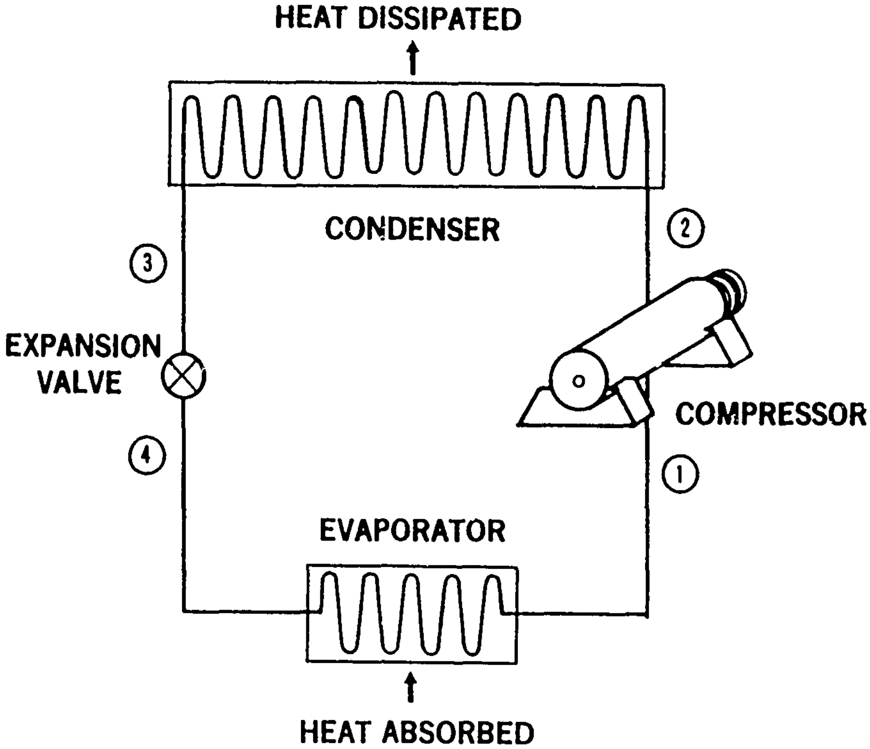

Figure 1. Typical conventional electromechanical cooling system.

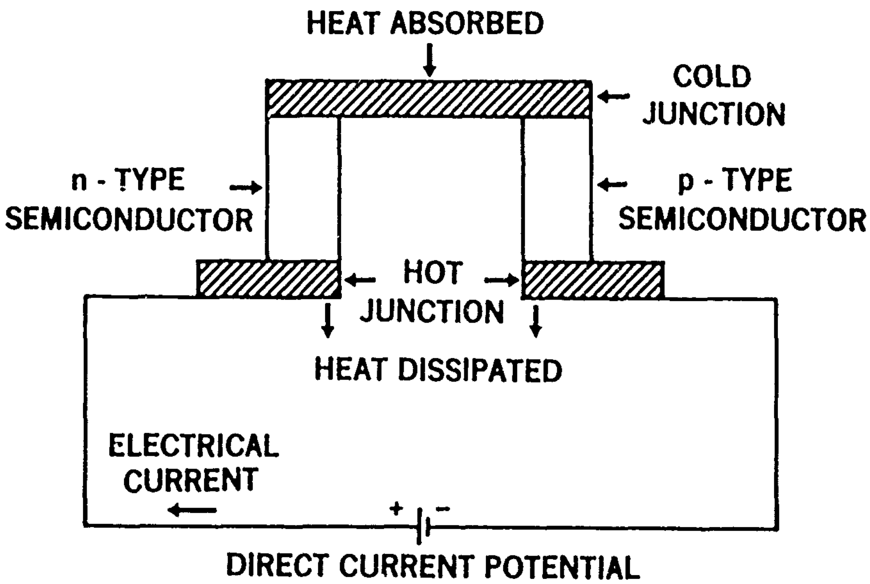

Figure 2. Typical thermoelectric element cooling system.

Comparison of Conventional Electromechanical Cooling and Thermoelectric Heat Pump Technologies

A comparison between conventional electromechanical cooling technology and thermoelectric heat pump systems was addressed at the Tenth International Congress on Cooling, held at Kodani, and the results have been reported in the literature (32,68,117).

The basis of conventional electromechanical cooling is the cooling medium (fluid), and its efficiency can be compared with that of the thermoelectric semiconductor material. Compression and expansion of the conventional electromechanical cooling medium in a thermodynamic cycle corresponds to the exchange of heat between a thermoelectric semiconductor element and the ambient. The mechanical losses that occur during a conventional electromechanical cooling medium's compression and expansion can be compared to the degradation of the thermoelectric semiconductor material's figure of merit (Z), which is a function of the material's junction contact resistances and dependency on temperature. Finally, the performance of a compressor in a conventional cooling system can be compared to the performance of the direct current power supply of the thermoelectric heat pump. The efficiency of each process or element (η_1 through η_4) is summarized in Table 1 (32,68,117):

TABLE 1. COMPARISON OF CONVENTIONAL ELECTROMECHANICAL COOLING AND THERMOELECTRIC HEAT PUMP TECHNOLOGIES

Technology	Efficiency η_1	η_2	η_3	η_4
Conventional	0.8 (cooling medium)	0.5 (compression/ expansion)	0.5 (mechanical losses)	0.6 (compressor)
Thermoelectric	0.1 (material)	0.9 (heat exchange)	0.7 (contact resistance)	0.7 (power supply)

If a thermoelectric heat pump were to have an identical overall performance efficiency representative of the present conventional electromechanical cooling system technology, the thermoelectric semiconductor material's figure of merit (Z) would have to increase from the current average value of 3×10^{-3} °K^{-1} to approximately 10×10^{-3} °K^{-1} (32,68,117). On the basis of present knowledge, the estimated value of Z for any material will not exceed 6×10^{-3} °K^{-1} (258-265).

Thus, to a considerable extent, the inherent capabilities and limitations of thermoelectric heat pumps are determined by the characteristics of the thermoelectric semiconductor material and fabrication process. Factors--such as temperature limitations, operating efficiency, reliability, durability, size, weight, configuration, power requirements, and cost--are all related to the fundamental thermoelectric semiconductor material and fabrication process. To provide a basis for evaluating the feasibility of using thermoelectric heat pump modules to dissipate the heat generated by the environment and human metabolism for a ground troop dressed in CW protective clothing, the important characteristics of thermoelectric materials are summarized here.

THERMOELECTRIC MATERIALS

Solid-state materials are generally classified by their electrical properties (metals, semiconductors, and insulators). The useful crystalline materials for thermoelectric elements are classified as semiconductors, having an electrical conductivity between metals and insulators. With respect to thermoelectric materials, the most important material characteristic--the figure of merit (Z)--describes the usefulness of a material by the following relationship (49-53,61,63-65,265-279):

$$Z = \frac{\alpha^2 \delta}{k} \tag{1}$$

where α = Seebeck coefficient

δ = electrical conductivity

k = thermal conductivity

As shown by Equation (1), control of the Seebeck coefficient, electrical conductivity, and thermal conductivity is essential to obtain a high figure of merit. In addition, all three quantities are a function of the density of free charge carriers (N_c) in the material (265-279).

Several investigators have shown that a semiconductor's figure of merit (Z) has a maximum value in the region where the free charge carrier density (N_c) is on the order of 10^{18} to 10^{21} carriers per cubic centimeter (265-279). The relationship of the three important thermoelectric material properties (α, δ, and k), as a function of the free charge carrier concentration (N_c), is shown in Figure 3 (277-293). The electrical conductivity (δ) increases with increasing carrier concentration (277,278,280-286). The thermal conductivity (k) has two components: a lattice thermal conductivity which is independent of the carrier concentration; and the electronic thermal conductivity which is proportional to the free charge carrier concentration (277-279,282-293). Thus, the difficulty in identifying an optimum thermoelectric material is now apparent. Insulators have large α's, but low electrical conductivities. Metals, on the other hand, have very small α's. The most favorable figure merit value corresponds to those α's, δ's, and k's characteristic of highly doped, near-degenerate semiconductors (semi-metals) (277-282,287-293).

In the selection of a thermoelectric semiconductor material, a large free charge carrier concentration (N_c) is desirable--one which, from a solid-state physics viewpoint, is associated with a low band-gap energy (E_g)

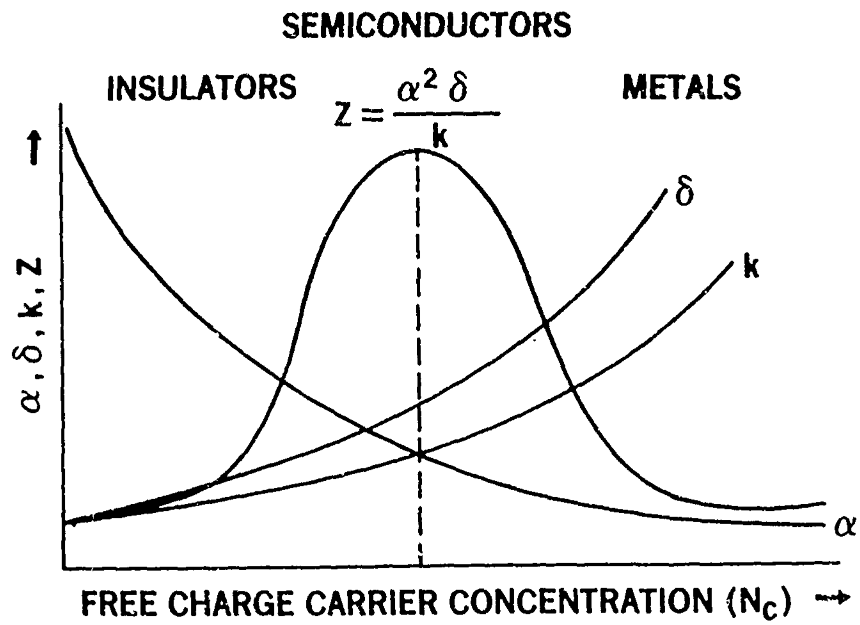

Figure 3. Thermoelectric material properties as a function of the free charge carrier concentration.

(292,293). Maximizing the band-gap energy is important, however, to avoid intrinsic conduction at the highest anticipated operating temperature. Extensive research has led to the discovery of several thermoelectric semiconductor materials. The common thermoelectric materials and their important physical properties are summarized in Table 2 (6,7,10,12,16,19,20,27,28,31,35,36,45, 49-52,54,55,59-63,66,67,73,74,81,114,116,118,119,254-256,277,280-286,288,289, 294-372).

For applications near ambient temperature (300°K), Bi_2Te_3, $BiSb_4Te_{7.5}$, and Bi_2Te_2Se are the best semiconductor materials for thermoelectric heat pump applications (295,299-302,305-309,313,314,316,334,342,346,357,363,368). Improvement in the techniques of solid solution alloying of $BiSb_4Te_{7.5}$ (p-type semiconductor) and Bi_2Te_2Se (n-type semiconductor) has been the principal factor that has advanced the state of the art for thermoelectric heat pump materials.

THEROMELECTRIC DEVICE PERFORMANCE AND THEORY

The thermoelectric phenomenon is the result of five distinct effects (Seebeck, Peltier, Thomson, Fourier, and Joule) that act concurrently (3,7, 8-16,24,27,31,40,45,49,57,62,68). The Seebeck, Peltier, and Thomson effects account for the reversible interchange of electrical and thermal energies. The Fourier and Joule effects account for the irreversible effects of heat evolution. A rigorous description of this subject is available in the literature (8-16). A summary of the important analytical relationships is presented, however, so that the problem of cooling a ground troop dressed in CW protective clothing can be evaluated on a quantitative basis.

A thermoelectric couple is an electrical circuit consisting of two different semiconductors connected in series (Fig. 4, Views a and b). The two semiconductors are n-type and p-type. An n-type semiconductor has an excess of electrons and is classified as having negative thermoelectric power. A p-type semiconductor has a deficiency of electrons (an excess of holes) and is classified as having positive thermoelectric power (3,7,8-16,27,68).

TABLE 2. KNOWN THERMOELECTRIC MATERIALS

Materials	Figure of merit (Z) (°K^{-1})	Lattice thermal conductivity (W•cm^{-1}•°K^{-1})	Electronic thermal conductivity (W•cm^{-1}•°K^{-1})	Semiconductor type	Operating temperature (°K)
Bi_2Te_3	2×10^{-3}	0.016	0.004	n or p	300
$BiSb_4Te_{7.5}$	3.3×10^{-3}	0.010	0.004	p	300
Bi_2Te_2Se	2.3×10^{-3}	0.013	0.003	n	300
PbTe	1.2×10^{-3}	0.02	0.003	n or p	300
Pb_2TeSe	1.3×10^{-3}	0.015	0.003	n	700
GeTe(+Bi)	1.6×10^{-3}	0.02	-----	p	800
ZnSb	1.2×10^{-3}	0.17	-----	p	500
$AgSbTe_2$	1.8×10^{-3}	0.006	0.002	p	700
MnTe	4×10^{-4}	0.013	-----	p	1000
InAs(+P)	6×10^{-4}	0.07	-----	n	900
CeS	4×10^{-4}	0.01	-----	n	1200
CeS(+Ba)	8×10^{-4}	0.01	-----	n	1200
ZnO	---------	----	-----	n	1500
Cu_2S	---------	----	-----	p	----
Cu_8Te_3	1.5×10^{-2}	0.012	-----	-------	1100
InTe	5×10^{-4}	-----	0.008	p	700
Ge-Si	9×10^{-4}	-----	0.033	n	1200
	6×10^{-4}	-----	0.033	p	1200

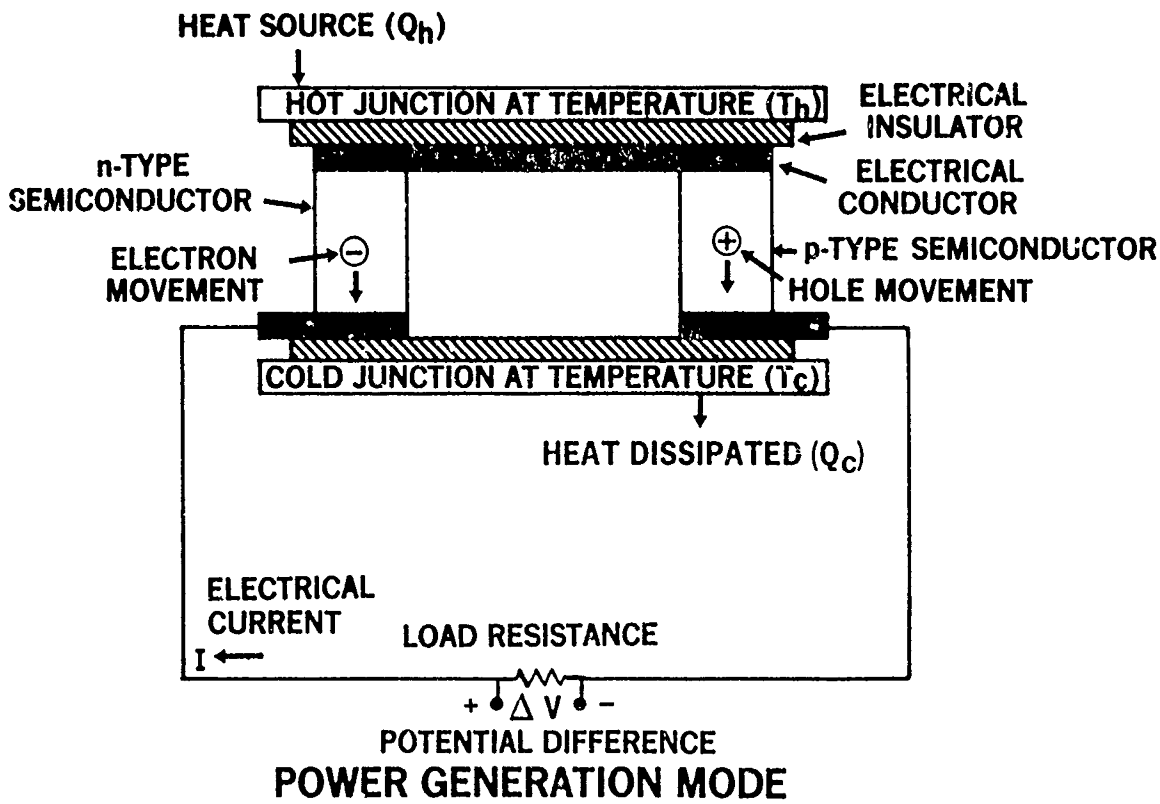

Figure 4: View a. Thermoelectric device operation: Power generation mode.

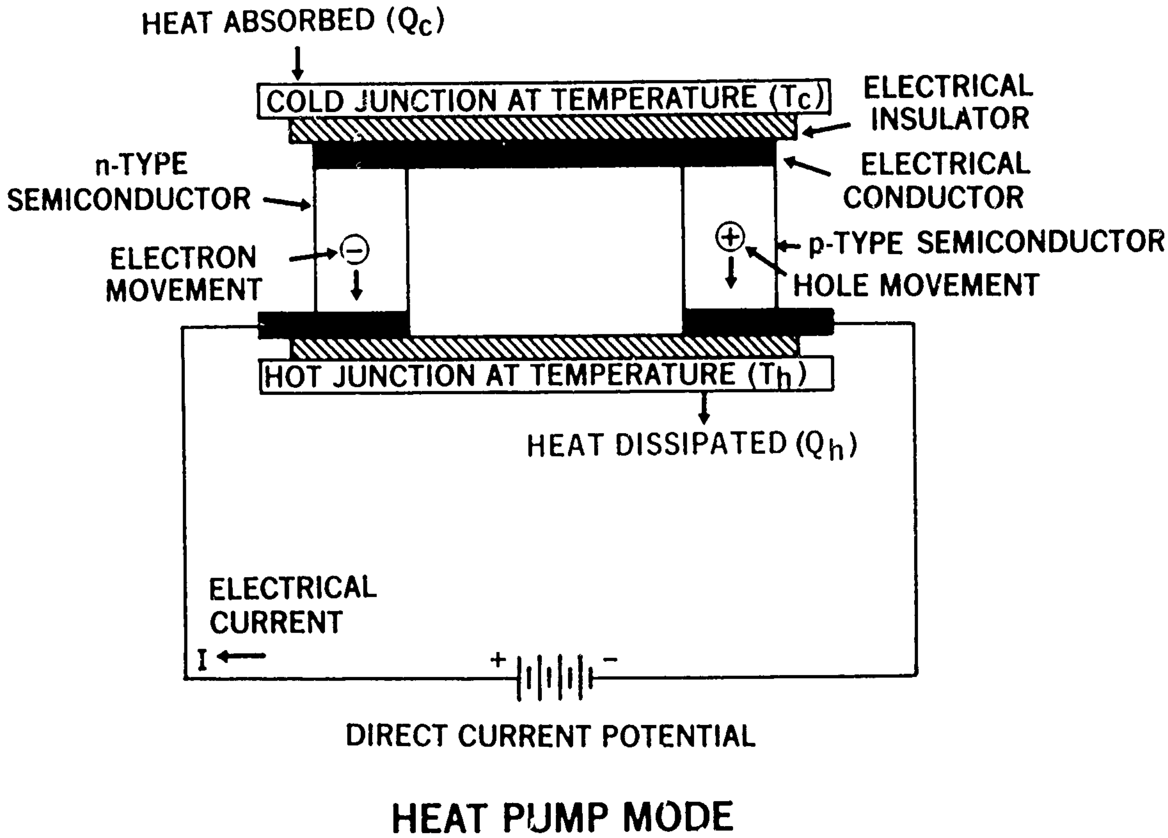

Figure 4: View b. Thermoelectric device operation: Heat pump mode.

Seebeck Effect

Thermoelectric power generation is the result of the Seebeck effect (8-16,373,374). As shown in Figure 4, View a (power generation mode), when the two dissimilar semiconductor junctions are maintained at different temperatures (T_c and T_h), a potential difference (ΔV) is created and results in a current flow (I). This open circuit potential difference can be expressed (8-16,373,374) as:

$$\Delta V = \alpha(T)[T_h - T_c] \tag{2}$$

in which $\alpha(T)$, the Seebeck coefficient of the two semiconductors, is given by:

$$\alpha(T) = \alpha_{p\text{-type}} - \alpha_{n\text{-type}} \tag{3}$$

Peltier Effect

Thermoelectric heat pumping, the principal phenomenon of interest in this Review, utilizes a reverse scheme known as the Peltier effect. In 1834, Jean C. A. Peltier discovered that the passage of an electrical current through the junction of two dissimilar conductors could either cool or heat a junction depending on the direction of the current (8-16,375-378). In addition, the heat generation or absorption rates (Q_c and Q_h) were proportional to the magnitude of the current and dependent on the temperature of the junction. In Figure 4, View b (heat pump mode), an electrical current (I) passes from the n-type semiconductor to the p-type semiconductor. The temperature of the cold junction (T_c) decreases, and heat is absorbed from the ambient. The heat absorption (cooling) occurs because electrons pass from a low energy level in the p-type semiconductor to a higher energy level in the n-type semiconductor. The absorbed heat is conducted through the semiconductor materials to the hot junction (T_h) by electron transport. The heat is then dissipated as the electrons return to a lower energy level in the p-type semiconductor. The quantity of heat absorbed (Peltier heat) at the thermoelectric junction is given by (8-16,375-378):

$$Q_p = \alpha(T)TI \tag{4}$$

where $\alpha(T)$ is the Seebeck coefficient of the two materials, T is the absolute temperature of the junction, and I is the current flowing through the junction.

Thomson Effect

As shown in Figure 5, the Thomson effect (differential Peltier effect) results in heating or cooling in a homogeneous material when an electrical current flows in the direction of a temperature gradient (3,7,8-16).

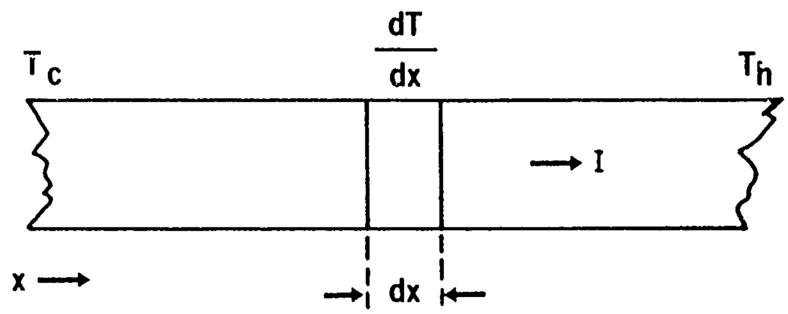

Figure 5. Thomson effect.

The Thomson heat per unit length of a material is given by (8-16):

$$Q_T = \tau(T) I \frac{dT}{dx} \tag{5}$$

for

$$\tau(T) = T \frac{d\alpha(T)}{dT} \tag{6}$$

where $\tau(T)$ is the Thomson coefficient of the material; I is the current flowing through the material; T is the absolute temperature; $\alpha(T)$ is the Seebeck coefficient of the material; and x is the position along the material in the direction of the current flow (I). If Q_T is the heat absorbed when the directions of I and $\frac{dT}{dx}$ coincide, then $\tau(T)$ is positive. If Q_T is the heat dissipated when the directions of I and $\frac{dT}{dx}$ coincide, then $\tau(T)$ is negative. In addition, it is obvious from Equation (6) that if the Seebeck coefficient [$\alpha(T)$] is independent of temperature, or a very weak function of temperature, the Thomson coefficient [$\tau(T)$] is zero or very nearly zero.

Fourier Effect

The Fourier effect (thermal conduction) of a material is due to the fact that a temperature gradient in a material induces a flow of heat in the direction of the negative temperature gradient (3,7,8-16). The rate at which heat is conducted across a unit surface of a material can be expressed (3,7,8-16) as:

$$Q_F = - k(T) \frac{dT}{dx} \tag{7}$$

for

$$k(T) = \left(\frac{k^*(T)_{p\text{-type}} A_{p\text{-type}}}{\ell_{p\text{-type}}}\right) + \left(\frac{k^*_{n\text{-type}} A_{n\text{-type}}}{\ell_{n\text{-type}}}\right) \tag{8}$$

where $k(T)$ is the net thermal conductivity of the materials; T is the absolute temperature; x is the position along the material in the direction of the flow of heat; A is the cross-sectional area of a material; ℓ is the length of a material; and $k^*(T)$ is the thermal conductivity of a material.

Joule Effect

Finally, the Joule effect occurs when a current flows through the resistance of an isothermal conductor. Joule heat is given by (3,7,8-16,24,40,45):

$$Q_J = I^2R(T) \tag{9}$$

for

$$R(T) = \left(\frac{\rho(T)^*_{p\text{-type}} \ell_{p\text{-type}}}{A_{p\text{-type}}}\right) + \left(\frac{\rho(T)^*_{n\text{-type}} \ell_{n\text{-type}}}{A_{n\text{-type}}}\right) \tag{10}$$

where I is the current flowing through the materials; $R(T)$ is the net electrical resistance of the materials; $\rho^*(T)$ is the resistivity of a material; ℓ is the length of a material; and A is the cross-sectional area of a material.

Thermodynamic Analysis

Thermodynamic analysis of a thermoelectric heat pump requires a relationship between the net heat absorbed at the cold junction and the net heat dissipated at the hot junction. The total heat flow across a thermoelectric junction is the sum of the heat flows due to Peltier heat (Q_p), Thomson heat

(Q_T), Fourier heat (Q_F), and Joule heat (Q_J). A heat balance equation for the cold junction in Figure 4 is:

$$Q_c = Q_P + Q_T - Q_F - Q_J \tag{11}$$

Similarly, a heat balance equation for the hot junction in Figure 4 is:

$$Q_h = Q_P - Q_T - Q_F + Q_J \tag{12}$$

Several practical and realistic assumptions are used to simplify the complex thermodynamic calculations (3,7,8-16,24,27,31,40,45,68):

a. Heat transfer between the hot and cold junctions to the ambient is perfect.
b. Thermal insulation in the thermoelectric device is perfect.
c. The thermoelectric device's junction resistance is negligible compared to the bulk resistance of the semiconductor material.
d. The electrical conductivity (δ), thermal conductivity (k), and Seebeck coefficient (α) of the semiconductor materials are independent of temperature.

With these assumptions, Equations (11) and (12) reduce to:

$$Q_c = Q_P - Q_F - Q_J \tag{13}$$

and

$$Q_h = Q_P - Q_F + Q_J \tag{14}$$

The Thomson heat (Q_T), given by Equation (5), is zero because of Equation (6) and the assumption that the Seebeck coefficient [$\alpha(T)$] is independent of temperature. Substitution of the more complex expressions for Q_P, Q_F, and Q_J yields:

$$Q_c = \alpha T_c I - k\Delta T - 1/2\ I^2R \tag{15}$$

$$Q_h = \alpha T_h I - k\Delta T + 1/2\ I^2R \tag{16}$$

Thermoelectric heat pumps may be designed from two approaches: maximize the coefficient of performance (Φ_{max}); or, maximize the heat pumping rate (Q_c max) (3,7,8-16,24,27,31,40,379). As will be shown, both of these parameters depend strongly on the operating temperature of the heat pump.

The coefficient of performance (Φ) is given by the ratio of the rate of heat removal from the cooled junction (Q_c) divided by the electrical input power (P) (7,8-16,31,379):

$$\Phi = \frac{Q_c}{P} \tag{17}$$

The heat pumping rate (Q_c) (refrigeration or cooling effect) is the rate at which heat is removed from the cold reservoir.

Maximum Coefficient of Performance

The rate of heat removal from the cold reservoir is given by Equation (15). From Figure 4 (heat pump mode), the applied voltage is:

$$V = \alpha\Delta T + IR \tag{18}$$

where

$$\Delta T = T_h - T_c \tag{19}$$

and the input power is:

$$P = VI \tag{20}$$

and from Equation (18):

$$P = \alpha . \Delta T + I^2R \tag{21}$$

or

$$P = \frac{V(V-\alpha\Delta T)}{R} \tag{22}$$

if Equations (20) and (21) are solved for I.

From Equations (15), (17), and (21), the coefficient of performance for the thermoelectric heat pump is:

$$\Phi = \frac{(\alpha T_c I - 1/2\ I^2 R - k\Delta T)}{(\alpha I \Delta T + I^2 R)} \tag{23}$$

If a new variable is defined such that

$$m = \frac{IR}{\alpha} \tag{24}$$

and Equation (24) is substituted into Equation (23), the coefficient of performance can be written as:

$$\Phi = \frac{[mT_C - 1/2\ m^2 - k\Delta T]}{(\alpha I \Delta T + I^2 R)} \tag{25}$$

The product of the thermal conductance and series resistance of the thermoelectric heat pump is, from Equations (8) and (10):

$$KR = k_{n\text{-type}}\rho_{n\text{-type}} + k_{n\text{-type}}\rho_{p\text{-type}} \left(\frac{A_{n\text{-type}}\ell_{p\text{-type}}}{A_{p\text{-type}}\ell_{n\text{-type}}}\right) +$$

$$k_{p\text{-type}}\rho_{n\text{-type}} \left(\frac{A_{p\text{-type}}\ell_{n\text{-type}}}{A_{n\text{-type}}\ell_{p\text{-type}}}\right) + k_{p\text{-type}}\rho_{p\text{-type}} \tag{26}$$

Equation (26) can be simplified by making the following substitutions:

$$k_{n\text{-type}} = k_n$$

$$k_{p\text{-type}} = k_p$$

$$\rho_{n\text{-type}} = \rho_n$$

$$\rho_{p\text{-type}} = \rho_p$$

$$\frac{A_{n\text{-type}}}{\ell_{n\text{-type}}} = \nu_n$$

$$\frac{A_{p\text{-type}}}{\ell_{p\text{-type}}} = \nu_p$$

Thus,

$$KR = k_n\rho_n + k_n\rho_p\left(\frac{\nu_n}{\nu_p}\right) + k_p\rho_n\left(\frac{\nu_p}{\nu_n}\right) + k_p\rho_p \tag{28}$$

Examination of Equations (25) and (28) reveals two variables which can be adjusted to maximize the coefficient of performance. These are the parameters m and the shape ratio $\left(\frac{\nu_n}{\nu_p}\right)$.

From a physical viewpoint of the purpose of a heat pump, the coefficient of performance is a positive quantity [Eq. (17)]; and the coefficient is maximized by minimizing the product KR. The value of $\left(\frac{\nu_n}{\nu_p}\right)$--which maximizes the coefficient--can be obtained by setting the partial derivative of KR with respect to $\left(\frac{\nu_n}{\nu_p}\right)$ equal to zero. The result is:

$$\left(\frac{\nu_n}{\nu_p}\right) = \left(\frac{\rho_n k_p}{\rho_p k_n}\right)^{1/2} \tag{29}$$

and the value of KR when $\left(\frac{\nu_n}{\nu_p}\right)$ has this value is:

$$KR_{min} = [(\rho_n k_n)^{1/2} + (\rho_p k_p)^{1/2}]^2 \tag{30}$$

The value of the coefficient of performance of the heat pump with this optimum geometry is:

$$\phi = \frac{[mT_C - 1/2\ m^2 - (\frac{\Delta T}{Z})]}{(m\Delta T + m^2)} \tag{31}$$

where the figure of merit (Z) is:

$$Z = \left\{\frac{\alpha}{[(\rho_n k_n)^{1/2} + (\rho_p k_p)^{1/2}]}\right\}^2 \quad (32)$$

The current which maximizes the coefficient of performance is found by setting the derivative of the coefficient of performance with respect to m equal to zero. The value obtained is:

$$I = \frac{\alpha\Delta T}{[R(\omega-1)]} \quad (33)$$

where

$$\omega = (1+Z\bar{T})^{1/2} \quad (34)$$

and

$$\bar{T} = 1/2(T_h+T_c) \quad (35)$$

At this value of current, the coefficient of performance of the heat pump is:

$$\phi_{max} = \left(\frac{T_c}{\Delta T}\right)\left\{\frac{[\omega-(\frac{T_h}{T_c})]}{(\omega+1)}\right\} \quad (36)$$

Thus, Equation (36) shows that the maximum coefficient of performance depends on the properties of the thermoelectric materials only through the figure of merit (Z). From Equations (18) and (33), the value of the applied voltage which maximizes the coefficient of performance is:

$$V = \frac{(\alpha\Delta T\omega)}{(\omega-1)} \quad (37)$$

Another significant fact is that the applied voltage is independent of the geometry of the thermoelectric heat pump. The power input, from Equation (22) is:

$$P = \left(\frac{\omega}{R}\right)\left[\frac{(\alpha\Delta T)}{(\omega-1)}\right]^2 \tag{38}$$

For completeness, the heat pumping rate with maximized coefficient of performance can be calculated using Equations (17), (36), and (38). However, the series resistance value of R must first be calculated for Equation (38). The shape ratio $\left(\frac{\nu_n}{\nu_p}\right)$, given by Equation (29), maximizes the coefficient of performance. The series resistance, defined by Equation (8), becomes:

$$R = \left(\frac{\alpha}{Z^{1/2}}\right)\left(\frac{1}{\nu_p}\right)\left(\frac{\rho_p}{k_p}\right)^{1/2} = \left(\frac{\alpha}{Z^{1/2}}\right)\left(\frac{1}{\nu_n}\right)\left(\frac{\rho_n}{k_n}\right)^{1/2} \tag{39}$$

Thus, the pumping rate is:

$$Q_c = \left(\frac{T_c}{\Delta T}\right)\left\{\frac{\left[\omega-\left(\frac{T_h}{T_c}\right)\right]}{(\omega+1)}\right\}\left[\left(\frac{\omega\nu_p Z^{1/2}}{\alpha}\right)\left(\frac{k_p}{\rho_p}\right)^{1/2}\right] \tag{40}$$

Maximum Heat Pumping Rate

The current for a maximum heat pumping rate can be obtained by taking the derivative of the heat pumping rate equation [Equation (15)] with respect to the current (I), and setting the result equal to zero. The current which maximizes the heat pumping rate is:

$$I = \frac{\alpha T_c}{R} \tag{41}$$

and the applied voltage, using Equation (18), is:

$$V = \alpha T_h \tag{42}$$

Thus, the maximum heat pumping rate at the current given by Equation (41) is:

$$Q_{c\ max} = \left(\frac{\alpha^2 T_c^{\ 2}}{2R}\right) - k\Delta T \tag{43}$$

In addition, as evident from Equation (43), the maximum temperature difference which a thermoelectric heat pump can produce (setting the derivative of $Q_{c\ max}$ with respect to I equal to zero) is:

$$\Delta T = \frac{\alpha^2 T_c^{\ 2}}{2RK} \tag{44}$$

Furthermore, ΔT can be maximized by minimizing KR. From Equations (30) and (32), ΔT_{max} is given by:

$$\Delta T_{max} = \frac{1}{2} Z T_c^{\ 2} \tag{45}$$

Fundamental Thermoelectric Heat Pump Design Philosophy

The design of a thermoelectric heat pump for a given application will probably be constrained with several boundary conditions. Representative of typical boundary conditions are: the magnitude of the heat load to be pumped; the temperature difference between the source and sink; the thermoelectric properties of the semiconductor materials; the contact resistivity of the thermoelectric element; the volume and space available; and the desirable economic features to be incorporated into the design. Even though a near complete set of boundary conditions might be available, the design of a thermoelectric heat pump is not completely straightforward. Many design problems stem from economic rather than technical considerations. The example in the following section emphasizes this point.

DESIGNING WITH THERMOELECTRIC HEAT PUMP TECHNOLOGY

Fundamentals to be Considered

A thermoelectric heat pump can be operated under two basic conditions (3,7,8-16,24,27,31,40,379):

a. the condition of maximum coefficient of performance (Φ_{max}), and
b. the condition of maximum heat pump capacity ($Q_{c\ max}$).

In the first case, the maximization of the coefficient of performance minimizes the electrical input power required to dissipate a given quantity of heat per unit of time, but maximizes the total number of thermoelectric heat pump elements needed for the system. In the second case, the maximization of the heat pump capacity maximizes the quantity of heat dissipated per unit of time, but at the expense of the electrical input power required to operate the system.

In the example design that follows, calculations are made for the two basic conditions. For a final design, the designer would optimize a hardware configuration somewhere between the two alternatives in order to accommodate such physical constraints as weight, volume, power supply requirements, and cost. The solution to this tedious problem, however, can conveniently be obtained using an iterative computerized technique--such as the Martin Marietta Thermal Analyzer System (MITAS)--that uses a lumped-parameter thermal network analysis method (380-381).

Statement of the Problem

As a result of the metabolic and environmental heat burden placed on a ground troop wearing CW protective clothing, a thermal conditioning system is needed to extend the time an individual can comfortably work in this environment. A possible technology for the thermal conditioning system is a thermoelectric heat pump. The potential for thermoelectric heat pumping is analyzed by modeling the human thermal conditioning problem (Fig. 6), as follows:

The design can be attacked in three phases. First, a certain amount of heat must flow from the reservoir (heat source) to the cold sink of the thermoelectric heat pump. Next, that same heat load plus an additional amount must be pumped through the module from the cold sink to the hot sink. In the last phase, heat must flow from the hot sink to some external reservoir (the ambient). The first and last phases require the application of heat-transfer laws, while the second phase requires use of the analytical thermoelectric principles presented in this Review.

As shown in Figure 6, an individual dissipates a known quantity of heat (Q_m) that is dependent on the metabolic rate. For this analysis, the metabolic rates and their associated average heat loads are summarized in Table 3 (382). Since the subject is dressed in CW protective clothing, stabilizing the individual's temperature (oral) (T_i) at a nominal 98.6°F (37°C) is desirable. Having the temperature of the air inside the protective clothing (T_s) equal to the temperature of the thermoelectric cold sink (T_c = 74°F or 23.3°C) is also desirable. The ambient temperature (T_a), external to the protective clothing, is 90°F (32.2°C) for this analysis (a realistic and typical value). The temperature of the heat sink (T_h) is 105°F (40.6°C) to optimize the thermoelectric heat pump performance and heat transfer to the ambient. The environmental heat load (Q_e) gained by a ground troop dressed in CW protective clothing is primarily the result of the radiant energy from the sun and sky, both that which is direct and that which is reflected and reradiated by the terrain. Adolph reports that, for an individual at rest, approximately 95 Calories/hr (Calorie = kilogram calorie and calorie = gram calorie) (23.9 BTU/hr or 110.4 W) are added to the thermal burden when the ambient temperature is 90°F (32.2°C) (383). The parameters illustrated in Figure 6, and the values selected for this analysis, are summarized in Table 4.

The design of the thermoelectric heat pump module is based on the material properties for industrial grade bismuth telluride (Bi_2Te_3). The material parameters are summarized in Table 5 (295,299,301,309,316,319,322,325,326, 329,336,343,347,363).

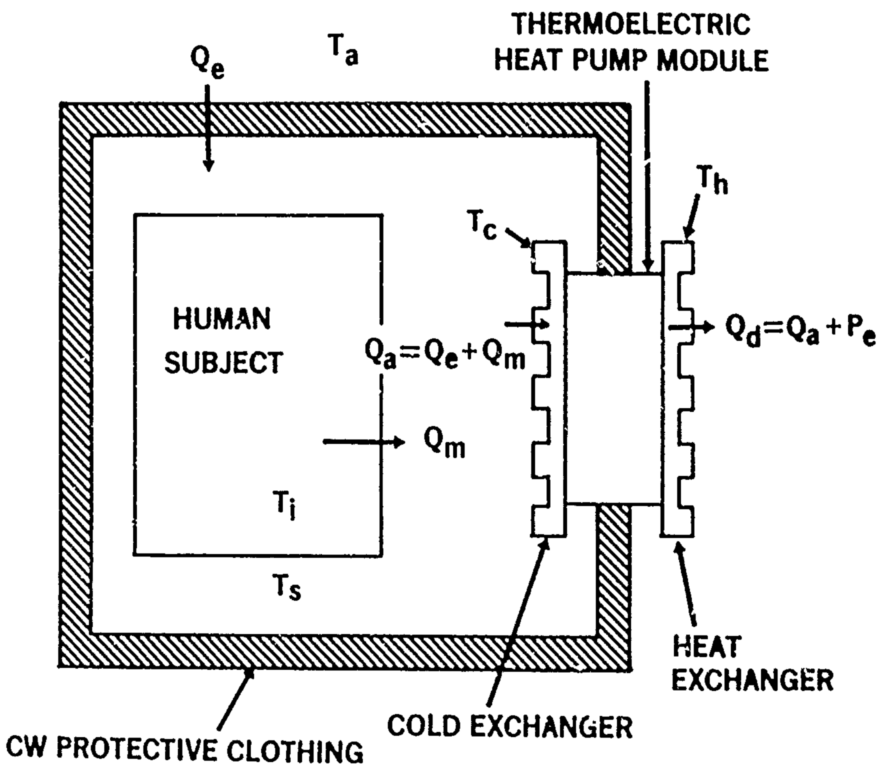

Figure 6. Model of the thermal conditioning problem for an individual dressed in CW protective clothing.

TABLE 3. HUMAN METABOLIC RATES AND THEIR ASSOCIATED AVERAGE HEAT LOADS

Metabolic Rate	Average Heat Load (Q_m)		
	(W)	(BTU/hr)	(Calories/hr)*
Rest	93	20.2	80
Light work	520	112.7	447.4
Moderate work	690	149.6	593.7
Heavy work	1035	224.4	890.5
All-out effort	1850	401.1	1591.8

*Calorie = kilogram calorie

TABLE 4. SUMMARY OF THE VALUES SELECTED FOR THE MODEL IN FIGURE 6

Parameter	Value
Q_a	$Q_e + Q_m$ (see Table 3)
Q_d	$Q_a + P_e$ (to be calculated)
Q_e	95 Calories/hr (23.9 BTU/hr)(110.4 W)
Q_m	(See Table 3)
T_a	90°F (32.2°C)(305.36°K)
T_c	74°F (23.3°C)(296.46°K)
T_h	105°F (40.6°C)(313.76°K)
T_i	98.6°F (37°C)(310.16°K)
T_s	74°F (23.3°C)(296.46°K)

TABLE 5. THERMOELECTRIC MATERIAL PROPERTIES

Parameter	Value
$\alpha_{n\text{-type}}$	$-232\ \mu V \cdot {}^\circ K^{-1}$
$\alpha_{p\text{-type}}$	$228\ \mu V \cdot {}^\circ K^{-1}$
$k_{n\text{-type}}$	$0.016\ W \cdot {}^\circ K^{-1} \cdot cm^{-1}$
$k_{p\text{-type}}$	$0.014\ W \cdot {}^\circ K^{-1} \cdot cm^{-1}$
$\rho_{n\text{-type}}$	1.11×10^{-3} ohm · cm
$\rho_{p\text{-type}}$	1.12×10^{-3} ohm · cm
$\ell_{n\text{-type}}$	0.125 in. (0.3175 cm)
$\ell_{p\text{-type}}$	0.125 in. (0.3175 cm)
$A_{n\text{-type}}$	4.91×10^{-2} in.^{2} (0.3167 cm^2)
$A_{p\text{-type}}$	4.91×10^{-2} in.^{2} (0.3167 cm^2)

Design for Maximum Coefficient of Performance

Since, in a number of case analyses, several of the results for specific calculations will be used, they will be made next and applied accordingly:

From Equation (3):

$$\alpha = [228 - (-232)]$$

$$\alpha = 4.6 \times 10^{-4} \text{ volts} \cdot {}^\circ K^{-1}$$

From Equation (8):

$$k = \left[\frac{(0.014)(0.3167)}{(0.3175)} + \frac{(0.016)(0.3167)}{(0.3175)}\right]$$

$$k = 2.99 \times 10^{-2}\ W \cdot {}^\circ K^{-1} \cdot cm^{-1}$$

From Equation (10):

$$R = \left[\frac{(1.12x10^{-3})(0.3175)}{(0.3167)} + \frac{(1.11x10^{-3})(0.3175)}{(0.3167)}\right]$$

$$R = 2.24 \text{ x } 10^{-3} \text{ ohms}$$

From Equation (19):

$$\Delta T = (313.76 - 296.46)$$

$$\Delta T = 17.3°K$$

From Equation (32):

$$Z = \left\{\frac{(4.6x10^{-4})}{[(1.11x10^{-3})(0.016)]^{1/2} + [(1.12x10^{-3})(0.014)]^{1/2}}\right\}^2$$

$$Z = 3.18x10^{-3}°K^{-1}$$

From Equation (35):

$$\overline{T} = 1/2(313.76+296.46)$$

$$\overline{T} = 305.11°K$$

From Equation (34):

$$\omega = [1 + (3.18x10^{-3})(305.11)]^{1/2}$$

$$\omega = 1.404$$

From Equation (36):

$$\Phi_{max} = \left(\frac{296.46}{17.3}\right)\left\{\frac{1.404-\left(\frac{313.76}{296.46}\right)}{1.404+1}\right\}$$

$$\Phi_{max} = 2.46$$

From Equation (33):

$$I = \frac{(4.6x10^{-4})(17.3)}{(2.24x10^{-3})(1.404-1)}$$

I = 8.794 amperes

From Equation (37):

$$V = \frac{(4.6x10^{-4})(17.3)(1.404)}{(1.404-1)}$$

V = 0.028 volts per couple

Finally, from Equation (38):

$$P = (\frac{1.404}{2.24x10^{-3}})[\frac{(4.6x10^{-4})(17.3)}{(1.404-1)}]^2$$

P = 0.246 W per couple

For each metabolic rate, a case analysis will be accomplished to determine the number of couples required to dissipate the heat load and the operating power supply voltage. The number of couples required to dissipate a given heat load is expressed as:

$$N = \frac{\text{Net heat to be pumped}}{\text{Heat pumped per couple}} \tag{46}$$

The operating supply voltage (V_o) is given by:

$$V_o = \text{(Voltage per couple)(Number of couples)}$$

or

$$V_o = VN \tag{47}$$

Case 1: Metabolic rate at rest (Q_m = 93 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 93$$

$$Q_a = 203.4 \text{ W}$$

From Equation (46):

$$N = \frac{203.4}{0.246}$$

$$N = 827 \text{ couples}$$

From Equation (47):

$$V_o = (0.028)(827)$$

$$V_o = 23.2 \text{ volts}$$

Case 2: Metabolic rate for light work (Q_m = 520 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 520$$

$$Q_a = 630.4 \text{ W}$$

From Equation (46):

$$N = \frac{630.4}{0.246}$$

$$N = 2563 \text{ couples}$$

From Equation (47):

$$V_o = (0.028)(2563)$$

$$V_o = 71.8 \text{ volts}$$

Case 3: Metabolic rate for moderate work (Q_m = 690 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 690$$

$$Q_a = 800.4 \text{ W}$$

From Equation (46):

$$N = \frac{800.4}{0.246}$$

$$N = 3254 \text{ couples}$$

From Equation (47):

$$V_o = (0.028)(3254)$$

$$V_o = 91.1 \text{ volts}$$

Case 4: Metabolic rate for heavy work (Q_m = 1035 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 1035$$

$$Q_a = 1145.4 \text{ W}$$

From Equation (46):

$$N = \frac{1145.4}{0.246}$$

$$N = 4657 \text{ couples}$$

From Equation (47):

$$V_o = (0.028)(4657)$$

$$V_o = 130.4 \text{ volts}$$

Case 5: Metabolic rate for all-out effort (Q_m = 1850 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 1850$$

$$Q_a = 1960.4 \text{ W}$$

From Equation (46):

$$N = \frac{1960.4}{0.246}$$

$$N = 7970 \text{ couples}$$

From Equation (47):

$$V_o = (0.028)(7970)$$

$$V_o = 223.2 \text{ volts}$$

Summarized in Table 6 are the important parameters for the maximum coefficient of performance design:

TABLE 6. MAXIMUM COEFFICIENT OF PERFORMANCE DESIGN

	Power Supply Requirements			
Metabolic rate	Current (amperes)	Voltage (volts)	Power (W)	No. of couples
Rest	8.794	23.2	204.1	827
Light work	8.794	71.8	631.4	2563
Moderate work	8.794	91.1	801.1	3254
Heavy work	8.794	130.4	1146.7	4657
All-out effort	8.794	223.2	1962.8	7970

Design for Maximum Heat Pump Capacity

Since, in a number of case analyses, several of the results for specific calculations will be used, they will be made next using applicable values calculated in the previous section:

From Equation (41):

$$I = \frac{(4.6\text{x}10^{-4})(296.46)}{(2.24\text{x}10^{-3})}$$

$$I = 60.9 \text{ amperes}$$

From Equation (42):

$$V = (4.6\text{x}10^{-4})(313.76)$$

$$V = 0.144 \text{ volts per couple}$$

From Equation (43):

$$Q_{c\ max} = [\frac{(4.6\text{x}10^{-4})^2(296.46)^2}{(2)(2.24\text{x}10^{-3})}] - (2.99\text{x}10^{-2})(17.3)$$

$$Q_{c\ max} = 4.15 \text{ watts per couple}$$

Case 1: Metabolic rate at rest (Q_m = 93 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 93$$

$$Q_a = 203.4 \text{ W}$$

From Equation (46):

$$N = \frac{203.4}{4.15}$$

$$N = 50 \text{ couples}$$

From Equation (47):

$$V_o = (0.144)(50)$$

$$V_o = 7.2 \text{ volts}$$

Case 2: Metabolic rate for light work (Q_m = 520 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 520$$

$$Q_a = 630.4 \text{ W}$$

From Equation (46):

$$N = \frac{630.4}{4.15}$$

$$N = 152 \text{ couples}$$

From Equation (47):

$$V_o = (0.144)(152)$$

$$V_o = 21.9 \text{ volts}$$

Case 3: Metabolic rate for moderate work (Q_m = 690 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 690$$

$$Q_a = 800.4 \text{ W}$$

From Equation (46):

$$N = \frac{800.4}{4.15}$$

$$N = 193 \text{ couples}$$

From Equation (47):

$$V_o = (0.144)(193)$$

$$V_o = 27.8 \text{ volts}$$

Case 4: Metabolic rate for heavy work (Q_m = 1035 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 1035$$

$$Q_a = 1145.4 \text{ W}$$

From Equation (46):

$$N = \frac{1145.4}{4.15}$$

$$N = 276 \text{ couples}$$

From Equation (47):

$$V_o = (0.144)(276)$$

$$V_o = 39.8 \text{ volts}$$

Case 5: Metabolic rate for all-out effort (Q_m = 1850 W)

From Figure 6 and Table 4:

$$Q_a = 110.4 + 1850$$

$$Q_a = 1960.4 \text{ W}$$

From Equation (46):

$$N = \frac{1960.4}{4.15}$$

$$N = 473 \text{ couples}$$

From Equation (47):

$$V_0 = (0.144)(473)$$

$$V_0 = 68.1 \text{ volts}$$

Summarized in Table 7 are the important parameters for the maximum heat pump capacity design:

TABLE 7. MAXIMUM HEAT PUMP CAPACITY DESIGN

	Power Supply Requirements			
Metabolic rate	Current (amperes)	Voltage (volts)	Power (W)	No. of couples
Rest	60.9	7.2	438.5	50
Light work	60.9	21.9	1333.7	152
Moderate work	60.9	27.8	1693.1	193
Heavy work	60.9	39.8	2423.8	276
All-out effort	60.9	68.1	4147.3	473

Discussed in the next section are the meaning of these calculations, and the problems one might encounter trying to implement them with hardware.

IMPLEMENTING A THERMOELECTRIC HEAT PUMP DESIGN

Comments on Design Calculations

The primary components of a thermoelectric cooling system are: the thermoelectric module design; the transfer of thermal energy between a thermoelectric surface and the ambient medium surrounding it; and the source of electrical energy to power the thermoelectric modules. The authors will use the results of the "moderate metabolic rate" condition to complete the analysis of a thermoelectric cooling system design. (This decision was made because the "moderate metabolic rate" represents an "average" workload for the problem at hand.)

Thermoelectric Module Design

A thermoelectric module is an assembly of several thermoelectric semiconductor elements (couples). By definition, a thermoelectric module is the smallest assembly of elements that can be physically interchanged as a unit in thermoelectric system (3,8-16,384). The number of elements in a module, or its heat pumping capacity, are not specified in the module definition.

The two basic types of thermoelectric modules are: electrically isolated, and electrically insulated (8-16,54,234).

The electrically isolated module is known as a direct transfer device. This module design divides the heat exchanger into segments, and each segment transfers heat from one side to its other side. A cross-sectional view of this design is shown in Figure 7. This design is used primarily in large air-conditioning applications.

The electrically insulated variant is the most common thermoelectric module design. In this type of module, a layer of electrical insulation is sandwiched between the thermoelectric elements and the heat exchanger base. Shown in Figure 8 is a cross-sectional view of a typical electrically insulated module. Since the layer of electrical insulation is directly in the heat path, this insulation must be a good thermal conductor; consequently, the range of materials is strictly limited (e.g., Mylar, glass, aluminum oxide, epoxy resin, mica, and silicon grease). The geometry (thin, flat, large planar surface area) makes this design a better choice for regulating the thermal burden imposed by CW protective clothing.

A typical commercially available module contains 44 of the elements (or 22 couples), is 1.5 in. by 1.5 in. by 0.25 in. thick (3.81 cm by 3.81 cm by 0.64 cm thick), weighs approximately 25 grams, and costs approximately $30/module (254-257). Summarized in Table 8 are the important parameters associated with the size, volume, and weight of the thermoelectric module for the metabolic rate requirements of moderate work.

As indicated in Table 8, the maximum heat pump capacity parameters would be very compatible with integrating the thermoelectric cooling system on the ground troop's back. The maximum coefficient of performance parameters is not as desirable. The surface area requirement approaches, if not exceeds, the surface area available on an average male's back; the weight of the thermoelectric modules exceeds 8 lb; and the cost is not realistic. Could optimization of the design by computer techniques produce a more cost effective and physically compatible (with the individual--particularly surface area and weight) design? The answer is probably "Yes."

Thermoelectric Module Heat Transfer

For normal operation of a thermoelectric cooling device, it is necessary to provide efficient heat coupling between the thermoelectric module and the area or volume to be thermally regulated on one hand, and with the heat transfer system on the other. The purpose of a heat transfer system is to dissipate heat from the hot junction of a thermoelectric module. The four basic types of heat transfer systems (385-406) are:

a. air on both sides,
b. air on cold side and fluid on hot side,
c. air on hot side and fluid on cold side, and
d. fluid on both sides.

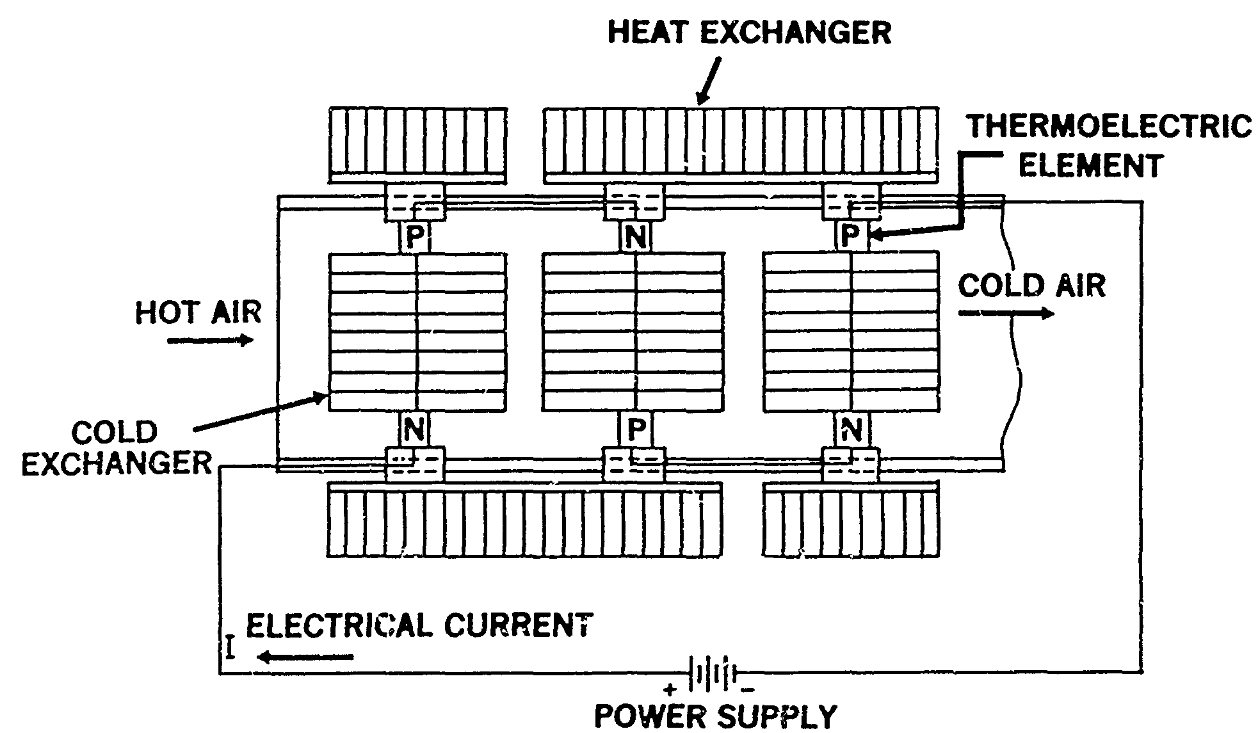

Figure 7. Electrically isolated thermoelectric module (cross-sectional view).

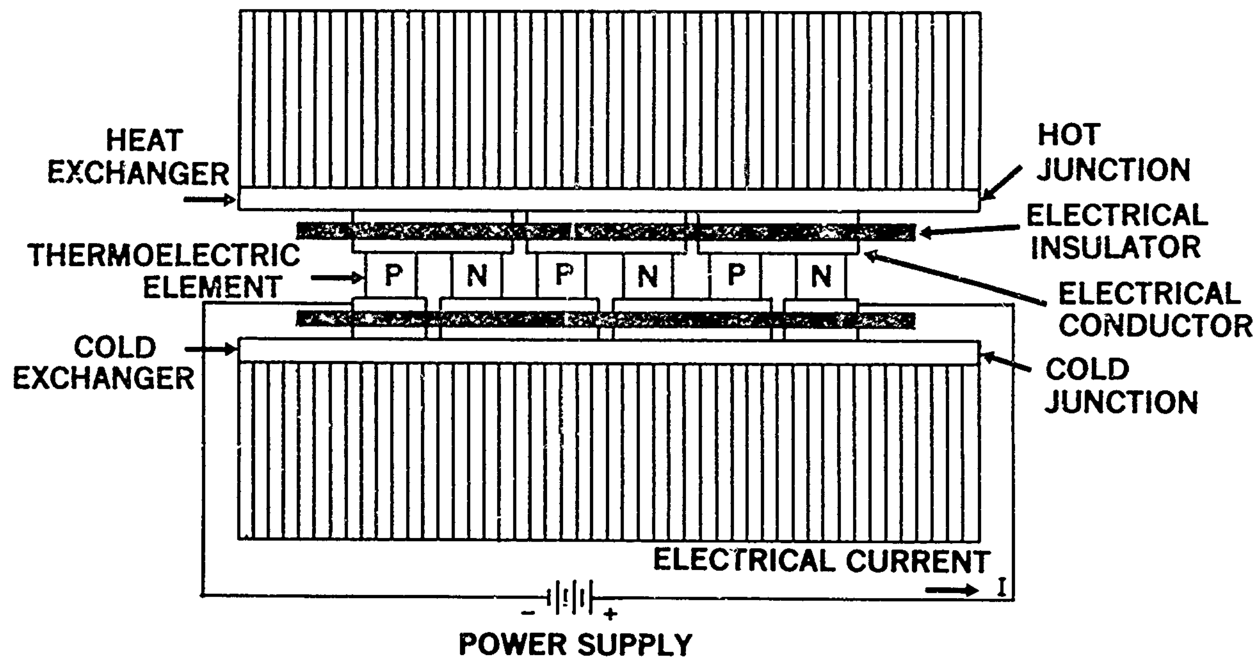

Figure 8. Electrically insulated thermoelectric module (cross-sectional view).

TABLE 8. THERMOELECTRIC MODULE PHYSICAL CHARACTERISTICS

Design	No. of modules	Surface area of modules (in.^{2}/cm^2)	Volumetric module displacement (in.^{3}/cm^3)	Weight of modules (grams)	Cost ($)
Maximum coefficient of performance	148	333/2148.4	83.25/1364.2	3700	$4400
Maximum heat pump capacity	9	20.25/130.7	5.1/83	225	$270

Each of these heat transfer systems has been considered for this cooling system design, and their respective advantages and disadvantages are summarized in Table 9 (386,391,392,397,398,401,402,404).

The "air on both sides" heat transfer system is the simplest technology. Since simplicity is of prime importance in the problem at hand, the author selected this system for more detailed analysis.

The "air on both sides" heat transfer process is a convective phenomenon. From Figure 6 and Equations (12), (14), and (16), the total heat flow (Q_h) at the hot junction must be dissipated from the thermoelectric cooling system for efficient operation. The convective heat transfer process (3,8-16,385, 387-389,403) is governed by the following equation:

$$Q_d = \eta \beta A b (T_h - T_a) \tag{48}$$

where η is the fin efficiency factor that accounts for the fact that the fins are not isothermal at their base temperature (T_h); β is the heat exchanger fin factor (equal to the ratio of total fin and plate area to the base plate area); A is the base plate area; b is the heat-transfer coefficient for free or forced convection; and T_a is the ambient temperature.

Representative ranges of values for these parameters (8-16,387-389) are:

a. $0.7 < \eta < 1.0$

b. $1.0 < \beta < 20.0$

c. A will be calculated ft^2

d. $0.5 < b < 1.0$ $BTU \cdot hr^{-1} \cdot ft^2 \cdot °F$ (free convection)

e. $2.0 < b < 5.0$ $BTU \cdot hr^{-1} \cdot ft^2 \cdot °F$ (forced convection)

f. $10.0 < (T_h - T_a) < 30.0$ °F

For the moderate metabolic rate considered in this analysis, the value of Q_d must be calculated. From Figure 6, Table 6, Table 7, and the values of Q_a calculated in the case analyses--the value of Q_d for maximizing the coefficient of performance is approximately 1600 W. Similarly, the value of Q_d for maximizing the heat pump capacity is approximately 2500 W.

TABLE 9. EVALUATION OF HEAT TRANSFER SYSTEMS

Type of system	Advantages	Disadvantages
Air on both sides	Lightest possible weight Simple design Easy to maintain	Complex air baffling Least efficient Uneven temperature distributions on exchangers Requires large surface area Hot side thermoelectric modules may overheat
Air on cold side and fluid on hot side	Moderate weight Hot side exchanger surface area can be reduced	Uneven temperature distribution on cold side Maintenance problems increased Noise level increases (pumps) Potential fluid leaks Requires more electrical power (pumps)
Air on hot side and fluid on cold side	Moderate weight Cooler hot exchanger Uniform temperature distribution on cold side	Uneven temperature distribution on hot side Maintenance problems increased Noise level increases (pumps) Potential fluid leaks Requires more electrical power (pumps)
Fluid on both sides	Isolation of thermoelectric module components from environmental contaminants Uniform temperature distribution on hot and cold sides	Most expensive Highest noise levels Highest weight Highest maintenance burden Potential for leaks Highest consumption of additional electrical power (pumps)

Summarized in Table 10 is the heat transfer surface area requirement for the moderate metabolic rate, for free and forced convection, and for selection of the optimum values for the parameters in Equation (48).

As can be observed from Table 10, the required surface areas for the heat transfer sinks are very large, and the associated weight would prohibit implementation with a human subject. Computer optimization of the thermoelectric module design would not resolve this problem. Perhaps one of the liquid transfer schemes would be of benefit, but then such objectives as simplicity and low cost would be compromised.

Power Supply

One of the primary components of a thermoelectric cooling system is the power supply. The selection of a power supply affects such factors in a thermoelectric module as configuration and design, duration of continuous operation, cost, and mass.

The current power supply technologies available for the production of electrical energy include chemical fuels, solar, radioisotopes, and storage batteries (407-416). The most suitable power supply technology for a portable thermoelectric cooling system is the storage battery.

Fundamentally, storage batteries are classified as "primary" if they cannot be recharged or are intended for a single discharge, and as "secondary" if they can be recharged or are intended to be charged or discharged (cycled a number of times). For the thermoelectric cooling system being analyzed, the secondary storage battery offers the most flexibility and long-term economics.

The important characteristics of the four major types of commercially available secondary storage batteries are summarized in Table 11 (417-430).

According to the characteristics in Table 11, the most suitable power supply for a portable thermoelectric cooling system is the silver-zinc secondary storage battery. This battery offers the most with respect to voltage, current delivery capability, and energy density.

Continuing with the design analysis, Table 12 was constructed using the optimum values for the silver-zinc battery and the power supply data in Tables 6 and 7 for the "moderate work" metabolic rate (417-430).

As shown in Table 12, the number of cells, their weight, and displacement are excessive relative to the number of hours they can be expected to perform at the rated load. Computer optimization of the thermoelectric cooling system design will not resolve this problem.

CONCLUSION

The theory, applications, and analysis of the problem of cooling a ground troop dressed in CW protective clothing have been addressed. The analysis has shown that the current thermoelectric cooling technology will not practically

TABLE 10. HEAT TRANSFER THERMAL SINK SURFACE AREA REQUIREMENTS

Design	Heat to be dissipated ($W/BTU \cdot hr^{-1}$)	n	β	Free convection (b)	Forced convection (b)	$(T_h - T_a)$ (°F)
Maximum coefficient of performance	1600/5461	1	20	1	5	15
Maximum heat pump capacity	2500/8532	1	20	1	5	15

TABLE 11. CHARACTERISTICS OF COMMERCIALLY IMPORTANT SECONDARY STORAGE BATTERIES

Characteristic	Gelled-electrolyte (lead acid)	Nickel-cadmium	Silver-cadmium	Silver-zinc
Voltage per cell	2	1.2	1.1	1.5
Capability	30mAh-25Ah	20mAh-10Ah	100mAh-50Ah	50mAh-60Ah
Energy density:				
W·hr/lb	8-10	12-6	22-34	40-50
W·hr/in.^{3}	1.1	1.3-1.7	1.5-2.7	2.5-3.2
Impedance	low	low	very low	very low
Discharge curve	sloping downward	flat	flat	flat
Temperature range (°F):				
Storage	-40 to 100	-40 to 140	-85 to 165	-85 to 165
Discharge	-76 to 140	-40 to 140	-10 to 165	-10 to 165
Charge	32 to 113	32 to 113	32 to 115	32 to 115
Cycle life (deep cycles)	1000	1500	200	50
Relative cost (Rated on a scale of 4 for maximum)	1	2	4	3

TABLE 12. POWER SUPPLY REQUIREMENTS

Design	Current (amperes)	Voltage (volts)	No. of cells	Weight (lb)	Displacement (in.^{3})	Hours of use at rated load
Maximum coefficient of performance	8.794	91.1	61	109	1703	6.8
Maximum heat pump capacity	60.9	27.8	19	30	476	0.9

or efficiently support the thermal regulation requirements for a human dressed in the CW protective clothing ensemble (for the temperature and thermal loads considered). However, before thermoelectric cooling is totally discarded, one final question should now be considered: If only a portion of the total thermal burden is removed, does thermoelectric cooling become more attractive and realistic? That is, if a thermoelectric cooling system is designed to be compatible with an individual from a physical viewpoint (mass, volumetric displacement, etc.), provided that the design will dissipate X watts, will the performance and length of time that an individual can work in the ensemble be marginally improved?

REFERENCES CITED

1. Abbott, M. M. Thermodynamics. New York: McGraw-Hill, 1972.

2. Guggenheim, E. A. Thermodynamics. Amsterdam: North-Holland Publishing Company, 1957.

3. Zemansky, C. Heat and thermodynamics. New York: McGraw-Hill, 1943.

4. Scofield, D. W., P. F. Taylor, and L. A. Staebler. A comparative study of the manufacturing costs of thermoelectric and mechanical refrigerating systems. ASHRAE J 2:37 (1960).

5. Van Wylen, G. J., and R. E. Sonntag. Fundamentals of classical thermodynamics. New York: John Wiley and Sons, 1965.

6. Burshtein, A. I. Physical basis for design for semiconductor thermoelectric devices. Moscow: Fizmatgiz Publishers, 1962.

7. Cadoff, I. B., and E. Miller. Thermoelectric materials and devices. New York: Reinhold, 1959.

8. Goldsmid, H. J. Applications of thermoelectricity. London: Methuen and Company Limited, 1960.

9. Goldsmid, H. J. Thermoelectric refrigeration. New York: Plenum Press, 1964.

10. Heikes, R. R., and R. W. Ure. Thermoelectricity: science and engineering. New York: Interscience Publishers, 1961.

11. Ioffe, A. F. Semiconductor thermoelements. Moscow: AN SSSR Press, 1960.

12. Ioffe, A. F. Semiconductor thermoelectric and thermoelectric cooling. London: Infosearch Limited, 1957.

13. MacDonald, D. K. Thermoelectricity: An introduction to the principles. New York: John Wiley and Sons, 1962.

14. Martynovskiy, V. S. Thermal pumps. Moscow: State Power Engineering Press, 1955.

15. Sze, S. Physics of semiconductor devices. New York: John Wiley and Sons, 1969.

16. Zener, C. Thermoelectricity. New York: John Wiley and Sons, 1960.

17. Ioffe, A. F. Semiconductor thermocouples. Moscow: Akademizdat Press, 1960.

18. Stecker, K. Thermoelectric cooling. Radio und Fernsehen 16:494 (1964). Available NTIS AD 800159, 30 Mar 1966.

19. Aoki, M., and Y. Suge. Thermoelectric cooling by bismuth telluride thermojunctions. J Appl Phys 29:363 (1960).

20. Cutler, M. Thermoelectric behavior of p-n junctions. J Appl Phys 32:222 (1961).

21. Parrott, J. E., and A. W. Penn. The design theory of thermoelectric cooling elements and units. Solid-State Electronics 3:91 (1961).

22. Rice, L. R. Thermoelectric cooling and its use. Solid-State Design 4:32 (1963).

23. Penrod, E. B. The bases of thermoelectric cold production. Kaltetechn 15:219 (1963).

24. Heaten, A. G. Thermoelectrical engineering. Proc IEEE 109:223 (1962).

25. Beer, A. C. Physics of thermoelectricity. Proc ARS Space Power Systems Conf, Santa Monica, CA, 26-30 Sept 1960.

26. Kolenko, E. A. Thermoelectric cooling devices. Moscow: Izd-vo Nauka, 1967.

27. Eichhorn, R. L. A review of thermoelectric refrigeration. Proc IEEE 51:721 (1963).

28. Wolfe, R. The physics of thermoelectricity. Semiconductor Products and Solid-State Technol 6:23 (1963).

29. Celent, C. Thermoelectricity--the state-of-the-art. Electronic Indust 18:66 (1959).

30. Lindenblad, N. E. Thermoelectric heat pumping. Elec Eng 77:802 (1958).

31. Beer, A. C. Physics of thermoelectricity. Progr Astronaut and Rocketry 3:3 (1961).

32. Boerdijk, A. H. Contribution to a general theory of thermocouples. J Appl Phys 30:1080 (1959).

33. Bean, T. E. Thermoelectric cooling. Indust Electronics 1:110 (1962).

34. Goldsmid, H. J. Thermoelectric and thermomagnetic cooling. Indust Electronics 1:441 (1963).

35. Whiting, G., and J. McKiernan. Thermoelectric devices. Mech Eng 92:27 (1970).

36. Navarro, M. G. The fundamentals of thermoelectric refrigeration. Rev Cienc Apl 17:126 (1963).

37. Zito, R. Dynamic behavior of a thermoelectric heat pump. Electro-Technol 71:64 (1963).

38. Seely, J. H. Solid-state cooling elements. Machine Design 44:105 (1972).

39. Gross, E. T. Efficiency of thermoelectric devices. Am J Phys 29:729 (1961).

40. Eichhorn, R. L. Thermoelectric refrigeration. Refrig Eng 66:31 (1958).

41. Niculescu, D. Cooling devices with semiconductors. Stud and Cercet Fiz 26:643 (1974).

42. Steiger, O. Operation of thermoelectrical cooling elements. Kaelte-techn 14:69 (1962).

43. Poslt, Z. Thermoelectric cooling. Sdelovaci Technika 7:248 (1964).

44. Ioffe, A. F., et al. Thermoelectric refrigerator. Kholodil'naya Tekh 33:62 (1956).

45. Ioffe, A. F. The revival of thermoelectricity. Sci Am 199:31 (1958).

46. Mole, C. J., D. V. Foster, and R. A. Feranchok. Thermoelectric cooling technology. IEEE Trans Industry Applications IA-8:108 (1972).

47. Ioffe, A. F., et al. On improving the efficiency of semiconductor thermoelements. Dokl Akad Nauk SSSR 106:981 (1956).

48. Grier, M. B. Lumped parameter behavior of the single-stage thermoelectric microrefrigerator. Proc IRE 47:1515 (1959).

49. Altenkirch, E. Elektrothermische kalteerzeugung und reversible elektrische heizung. Z Physik 12:920 (1911).

50. Rice, W., and E. Flam. Design data for semiconductor thermoelectric devices. Electro-Technol 71:132 (1963).

51. Anatychuk, L. I., et al. Method for optimizing thermoelectric cooling devices. Power Eng 15:145 (1977).

52. Alfonso, N. Transient and steady-state theory of semiconductor thermoelectric cooling cells. Thesis, Carnegie Institute of Technology, Pittsburgh, PA, 1959.

53. Blatt, F. T. On the possibility of thermoelectric refrigeration at very low temperatures. Phil Mag 7:715 (1962).

54. Clingman, W. H. New concepts in thermoelectric devices design. Proc IRE 49:1155 (1961).

55. Ioffe, A. F., and L. S. Stil'bans. Physical problems of thermoelectricity. Report Progr Phys 22:167 (1959).

56. Norwood, M. H. A comparison of theory and experiment for a thermoelectric cooler. J Appl Phys 32:2559 (1961).

57. Hida, H., et al. Cascading of cooling junctions in thermoelectric refrigeration. J Appl Phys (Japan) 26:608 (1957).

58. Rezek, G. Thermal design and analog representation of a thermoelectric refrigerator. IEEE Int Convention Rec 11:188 (1963).

59. Gelbtuch, A., and C. A. Macphee. Design curves aid proper utilization of thermoelectric devices. Can Electronics Eng 5:32 (1961).

60. Talaat, M. E. Electric analog of thermoelectric generators. Adv Energy Conversion 2:167 (1962).

61. Kotyrlo, G. K., et al. Heat circuits of thermoelectric devices. Translation 23-853-74, USA Foreign Science and Technology Center, Charlottesville, VA. Available NTIS AD A000997, 19 July 1974.

62. Watanobe, A. Unified performance calculations for thermoelectric cooling. J Appl Phys 33:130 (1962).

63. Melehy, M. A. Theory of minority carrier thermoelectric cooling. J Appl Phys 33:2100 (1962).

64. Belevtsev, A. T., et al. Determination of the parameters of thermoelectric systems. Appl Solar Energy 11:8 (1975).

65. Sherman, B., R. R. Heikes, and R. W. Ure. Calculation of efficiency of thermoelectric devices. J Appl Phys 31:1 (1960).

66. Belevtsev, A. T., et al. Determination of the parameters of thermoelectric systems. Geliotekhnika 11:13 (1975).

67. Jasinski, R. J., and F. Wald. Study of thermoelectric and thermionic power conversion. Final report 277-024, USN Office of Naval Research, Washington, DC. Available NTIS AD 661455, Nov 1967.

68. Poslt, Z. Thermoelectric cooling. Report FTD-TT-65-1762, Foreign Technology Division, Wright-Patterson AFB, OH. Available NTIS AD 641105, 12 Apr 1966.

69. Kolenko, Y. A. Thermoelectric cooling devices. Report FSTC-HT-23-435-68, USA Foreign Science and Technology Center. Available NTIS AD 691974, 26 June 1969.

70. Green, W. B. (ed). Thermoelectric handbook. Westinghouse Corp., Youngwood, PA, 1962.

71. Timberlake, A. B., and T. S. Shilliday. Thermoelectric and thermomagnetic cooling. Report RSIC-487, USA Redstone Scientific Information Center, Redstone Arsenal, AL. Available NTIS AD 478668, Oct 1965.

72. Zorin, I. V., and Z. Y. Zorina. Thermoelectric coolers and generators. Translation FTD-HC-23-2126-74, Foreign Technology Division, Wright-Patterson AFB, OH. Available NTIS AD A007174, 21 Jan 1975.

73. Lougher, E. H., et al. Development of improved thermoelectric cooling materials for ground air conditioners. Final report AFAPL-TR-66-137, Wright-Patterson AFB, OH, 20 Jan 1967.

74. Lougher, E. H., E. P. Stambaugh, and W. D. Lemke. The application of advanced thermoelectric materials technology to military ground air conditioners. Technical Report AFAPL-TR-67-163, Wright-Patterson AFB, OH. Available NTIS AD 826048, Jan 1968.

75. Good, F. P. Nominal 24,000 BTU/hr air-to-air thermoelectric environmental control unit. Final report 1939, USA Mobility Equipment Research and Development Center, Fort Belvoir, VA. Available NTIS AD 684928, Feb 1969.

76. Good, F. P. Thermoelectric environmental control unit. Final report DA-44-009-1685, US Army Mobility Equipment Research and Development Center, Fort Belvoir, VA. Available NTIS AD 684928, Feb 1969.

77. Bernard, A. M., and L. J. Fox. Development of thermoelectric heating and ventilating system. Final report DA-19-129-QM-1981, US Army Headquarters Quartermaster Research and Engineering Command, Natick, MA. Available NTIS AD 644917, 15 Apr 1965.

78. Hudelson, G. D., G. K. Gable, and A. A. Beck. Thermoelectric environmental control unit. Final report DA-44-009-AMC-1135, US Army Engineer Research and Development Laboratories, Fort Belvoir, VA. Available NTIS AD 477479, 27 Sept 1965.

79. Stillivagon, R. E., T. J. Dzakowic, W. F. Briley, and G. T. Kartsovnses. Thermoelectric environmental control unit. Final report DA-44-009-AMC-1136, US Army Engineer Research and Development Laboratories, Fort Belvoir, VA. Available NTIS AD 477483, 8 Oct 1965.

80. Nolan, R. M. Sun to cool spaceship electronic components. Missiles and Rockets 4:40 (1958).

81. Bulman, W. E. Development of an active thermal control coating for space application. Final report DCN-3-1-50-23547 (1F), NASA Contract NAS8-24928, Jan 1970.

82. Webb, P., J. F. Annis, and S. J. Troutman. Automatic control of water cooling in space suits. NASA Contractor (Technical) Report, NASA-CR-1085, June 1968.

83. Little, E. P. Cooling of avionic equipment by thermoelectric methods. IEEE Trans Aerospace 2:702 (1964).

84. Standon, S. Thermopile held advancing IR detection capabilities. Electronics News 8:391 (1963).

85. Boesen, G. F., A. D. Reich, and C. E. Rufer. Infrared cell electronically refrigerated. Final report ASD-TR-61-369, Aeronautical Systems Div., Wright-Patterson AFB, OH, Sept 1961.

86. Anderson, J. R. Thermoelectric air conditioner for submarines. RCA Rev 22:292 (1961).

87. Phillips, A. F. Thermoelectric air conditioning and refrigeration for submarines. Proc Int Refriq Meeting, Washington, DC, 20-25 Aug 1962.

88. Grier, M. B. Wide use foreseen for applied thermoelectricity. Space/ Aeronautics 31:46 (1959).

89. Sickert, R. G. A thermoelectric refrigerating system for submarines. Elec Eng 79:364 (1960).

90. Gibson, H. F. Peltier heat pumps--application parameters and device possibilities. Technical report 902, Diamond Ordnance Fuze Laboratories. Available NTIS AD 250772, 7 Jan 1961.

91. First thermoelectric cooler. Materials in Design Eng 55:13 (1962).

92. Klein, P. H. Thermodynamics of thermoelectric refrigeration. Proc Int Refrig Meeting, Washington, DC, 20-25 Aug 1962.

93. MacDonald, D. K. Thermoelectricity at very low temperatures. Sci 129:943 (1959).

94. MacDonald, D. K., et al. On the possibility of thermoelectric refrigeration at very low temperatures. Philosoph Mag 4:433 (1959).

95. McCormick, J. E. Cryogenic thermoelectric cooling. Technical note 61-54, Rome Air Development Center, NY. Available NTIS AD 259770, May 1961.

96. Kluth, H. Possibilities in thermoelectric cooling. Industriekurier Techn und Forsch 15:269 (1962).

97. Lautz, G. Thermoelectric effects and the possibilities of their practical application. Math-Phys Semesterber 10:14 (1963).

98. McLean, I. Solid-state cooling system impractical AF study shows. Electronics News 9:58 (1964).

99. KiKuchi, M., and T. Izuka. The experiment of the thermoelectric refrigeration by Bi_2Te_3. Electrotechn Lab Japanese Bull 23:671 (1959).

100. Kirby, G., M. Norwood, and R. Marlow. Construction and evaluation of a thermoelectric controlled temperature chamber. Adv Energy Conversion 2:265 (1962).

101. Blatt, F. J. On the possibility of thermoelectric refrigeration at very low temperatures. Technical report AFOSR-1703, USAF AFOSR, Bolling AFB, Washington, DC. Available NTIS AD 267633, Nov 1961.

102. Stubstad, W. R. The application of thermoelectric spot cooling to electronic equipment. IRE Trans PEP 5:22 (1961).

103. Thermoelectric cooler module application consideration. Electromech Design 8:54 (1964).

104. Thermoelectric cooling improves noise figure. Electronics 33:86 (1960).

105. Uenahara, M., and R. Wolfe. Parametric amplifier with thermoelectric refrigeration. IRE Trans ED 8:521 (1961).

106. Khasimoto, A., T. M. Khitati, and K. Kaysya. A thermoelectric refrigerator with a device for controlling the temperature. Japanese Patent 13591, 1961.

107. Crowley, I. C. A cooled microscope stage using semiconductor thermoelectric cooling. J Sci Instrum 40:330 (1963).

108. Gerthsen, P. J., A. A. Gilsing, and M. Til. An automatic dew point device with Peltier cooling. Phillips Tech Rundschau 27:211 (1959).

109. Landay, I. Thermoelectric thermostat. Rev Sci Instrum 33:1004 (1962).

110. Love, C. C. Liquid hydrogen storage parameters for a lunar voyage. Paper AE60-0848, Fifth Symp Ballistic Missile and Space Technol, San Diego, CA, 29 Aug 1960.

111. Chapter, J. J., and G. W. Johnson. Thermoelectric device application to spacecraft thermal control. J Spacecraft and Rockets 11:159 (1974).

112. Levine, S. N. Selected papers on new techniques for energy conversion. New York: Dover Publications, 1961.

113. Bernard, A. M., and L. J. Fox. Development of thermoelectric heating and ventillating system. Final report WAED 65.26E, USA Headquarters Quartermaster Research and Engineering Command, Natick, MA. Available NTIS AD 644917, 15 Apr 1965.

114. Faus, H. T., and D. E. Ridgley. Tellurium-bismuth thermoelectric element. USA Patent 2,788,382, 9 Apr 1957.

115. Krieser, T. P. Thermoelectricity--power supply and control. IEEE Int Conv Rec 11:37 (1963).

116. Goldsmid, H. J. Thermoelectric applications of semiconductors. J Electronics 1:218 (1955).

117. Mueller, H. Construction and installation of Peltier aggregates in cooling devices. Siemens Zeitung 37:383 (1963).

118. Heaton, A. G. Thermoelectric cooling material characteristics and applications. Proc IEEE 110:1277 (1963).

119. Jaklovzky, J., et al. Thermoelectric materials and their applications. Electrotech Electron and Autom and Electron 26:305 (1978).

120. Anatychuk, L. I., et al. Investigation into thermoelectric microrefrigerators with limited heat transfer. Izv Vuz Priborostr 21:116 (1978).

121. Landecker, K. A two-stage refrigeration and power producing arrangement consisting of a vortex cooling tube and a thermoelectric stage. Energy Conversion 17:119 (1977).

122. Harpster, J. W. Improved spacecraft heat rejection with practical thermoelectric materials, p. 126. Proc Third Int Conf Thermoelectric Energy Conversion, Arlington, TX, 12-14 Mar 1980.

123. Norman, R. M. Cooling radioisotope thermoelectric generators in the shuttle. Proc 13th Intersociety Energy Conversion Eng Conf, San Diego, CA, 20-25 Aug 1978.

124. Stimpson, L. D., and D. I. Levine. Radioisotope thermoelectric generator cooling in the shuttle bay. Proc 14th Intersociety Energy Conversion Eng Conf, Boston, MA, 5-10 Aug 1979.

125. Vella, G. J., L. B. Harris, and H. J. Goldsmid. A solar thermoelectric refrigerator. Solar Energy 18:355 (1976).

126. Lunar electricity. Mech Eng 92:40 (1970).

127. Switching semiconductor unit turns chamber from hot to cold. Product Eng 17:47 (1971).

128. Brittain, W. M. SNAP 19 Viking RTG flight configuration and integration testing. Proc 9th Intersociety Energy Eng Conf, San Francisco, CA, 26-30 Aug 1974.

129. Tools get thermoelectric chill. Iron Age 190:107 (1962).

130. Hurwitz, M. Thermoelectric devices and appliances introduced by Borg-Warner. Solid-State Design 3:51 (1962).

131. Crawley, D. J. Thermoelectrically cooled baffles in conjunction with water and air-cooled diffusion pumps. Vide 19:641 (1964).

132. Jean, R., and R. Liot. Traps using the Peltier effect. Vide 17:186 (1962).

133. Guczi, L., and H. J. Tyrrell. The maintenance of controlled temperature differences using a thermoelectric heat pump. J Sci Instrum 41:468 (1964).

134. Crawley, J. C. A cooled microscope stage using semiconductor thermoelectric cooling. J Sci Instrum 40:330 (1963).

135. Griffin, O. G., and C. M. Stringfield. A dew point meter based on thermoelectric cooling. J Sci Instrum 41:241 (1964).

136. Ivanov, A. M., A. Kolenko, and I. Poltinnikov. A thermoelectric cataract cryoextractor. Soviet Patent 126629, 1964.

137. Price, D. L., and I. Levin. New biological warm stage. Am J Trop Med Hyg 10:755 (1961).

138. Fortier, I. R., and C. S. Thompson. Cooling transistors with thermoelectric elements. New York: McGraw-Hill, 1963.

139. Jeanes, R. V., and K. E. Pitt. Thermoelectrically cooled probe for the determination of semiconductor type. J of Sci Instrum 38:33 (1961).

140. Lautz, G. Thermoelectric temperature stabilization of an electrical circuit element. ETZ A80:741 (1959).

141. Nagata, M., and A. Zenemon. Thermoelectric elements for circuit cooling. Electronics 34:54 (1961).

142. Goldsmid, H. J., and R. W. Douglas. The use of semiconductors in thermoelectric refrigeration. Br J Applied Phys 5:386 (1954).

143. Stillwagon, R. E., et al. Thermoelectric environmental control unit. Final report WCD-40001-AC, USA Engineer Research and Development Laboratories, Fort Belvoir, VA, 8 Oct 1965.

144. Longstreet, C. S., et al. An evaluation of thermoelectric cooling as applied to engine control electronics. Final report AFAPL-TR-77-24, USAF Aero Propulsion Laboratory, Wright-Patterson AFB, OH. Available NTIS AD A042378, May 1977.

145. Martynovskiy, V. Low temperature thermoelectric refrigerator. Translation K2591, USA Foreign Science and Technology Center, Charlottesville, VA. Available NTIS AD 764171, 9 Aug 1973.

146. Nayer, B. A., et al. Semiconductor microcooler. Translation T702301, USA Foreign Science and Technology Center, Charlottesville, VA. Available NTIS AD 772455, 26 July 1973.

147. Ramert, B. A thermocouple. Czechoslovakian Patent 121300, 7 Oct 1964. Available NTIS AD 861420, 18 Nov 1969.

148. Weissman, Y. Optimization of a multistage thermoelectric refrigerator using the asymptotic temperature distribution. Appl Phys Letters 35:568 (1979).

149. High efficiency, low power, thermoelectric coolers. Technical report C0016, Marlow Industries Incorporated, Garland, TX. Available NTIS AD A083225, Dec 1979.

150. Bertrem, C. J., and F. H. Fujimoto. Detailed engineering design - thermoelectric environmental control unit. Design report L-8028, The Garrett Corporation, Airesearch Mfg. Div., Los Angeles, CA. Available NTIS AD 477492, 12 Nov 1965.

151. Sochard, I. I. Design and construction of a Peltier temperature-control device. Adv Energy Conversion 2:255 (1962).

152. Thermoelectric cooling unit. Engr 20:809 (1960).

153. Tseng-shou, L. The application of semiconductor refrigeration. K'o-hsuch Hsin-wen, Sci News 29:7 (1959).

154. Uemura, K. Cascade thermoelectric cooling. J Appl Phys (Japan) 29:377 (1960).

155. Wheeler, L. J. The design and application of Peltier coolers. Electronics Rev 170:663 (1962).

156. McDermott, J. Thermoelectric coolers tackle jobs heat sinks can't. Electronics Design News 25:111 (1980).

157. Swain, G. Experiment with Peltier effect devices. Electron Aust 41:40 (1979).

158. Field, R. L. Photovoltaic/thermoelectric refrigerator for medicine storage for developing countries. Proc 14th Intersociety Energy Conversion Eng Conf, Boston, MA, 5-10 Aug 1979.

159. Horst, R. B., and L. R. Williams. Application of solid-state cooling to spaceborne infrared focal planes. Proc Third Int Conf on Thermoelectric Energy Conversion, Arlington, TX, 12-14 Mar 1980.

160. Domke, K. Thermoelectric triple sensor for on-off control of temperature in electric furnaces. Elektrowaerme Int Ed 38:B130 (1980).

161. Silvestri, M., and P. Lucardesi. Peltier elements' constructional examples. Elettrificazione 3:123 (1976).

162. Rosen, A. D. A thermoelectric probe for focal cortical hypothermia. Electroencephalogr Clin Neurophysiol 40:106 (1976).

163. Elfving, T. M. The construction and operation of an air-cooled thermoelectric refrigerator. Kaltetechn 14:76 (1962).

164. Hudelson, G. D. Thermoelectric air conditioning of totally enclosed environments. Electrical Eng 79:460 (1960).

165. Ott, L. H. Electronic cooling and heating. Radio Electronics 33:26 (1962).

166. Sickert, R. G. A thermoelectric refrigerating system for submarines. Elec Eng 79:364 (1960).

167. Kolenko, Y. A., et al. An automatic device with cyclic operation for the determination of the solidification point of fuels. Soviet Patent 151865, 1962.

168. Kolenko, Y. A., et al. A miniature thermoelectric refrigerator for stock raising. Soviet Patent 122077, 1959.

169. Rosi, F. D. Thermoelectric couple. USA Patent 2,902,528, 1 Sept 1959.

170. Busanovich, C. J. Thermoelectric materials and elements utilizing them. USA Patent 2,902,529, 1 Sept 1959.

171. Contemporary instrumentation--frigitrons and their application. C R Nature Sci Prog 3341:387 (1963).

172. Makow, D. M. Portable thermoelectric pump controls heating or cooling of single component. Can Electronics Eng 7:26 (1963).

173. Masuda, S., and M. Yukio. Thermoelectric cooling element as thermal conductivity meter. Bull J SME 6:251 (1963).

174. Morioka, G. Thermoelectric cooling and its applied products. Radio and TV 5:24 (1962).

175. Ewen, W. Thermoelectrics, an application. Nat Telecommun Conf, Atlanta, GA, 26-28 Nov 1973.

176. Naer, V. A., et al. Thermoelectric cascade-type microrefrigerators. Geliotekhnika 9:78 (1973).

177. Basmajian, J. V., et al. Device for controlled rapid localized cooling. Am J Phys Med 52:65 (1973).

178. Antonov, Y. I., et al. Device for cooling radiation sensors. Report JPRS-55607, Joint Publications Research Service, Washington, DC, 3 Apr 1972.

179. Kline, W. G. Performance evaluation of thin layer thermoelectric device. Final report TR-2195, Naval Avionics Facility, Indianapolis, IN. Available AD A045361, 19 Oct 1977.

180. NiKolaev, Y. D., et al. Transport air coolers with standardized thermoelectric batteries. Kholodil'naya 5:16 (1971). Available NTIS AD 781012, 3 May 1974.

181. Gasser, F. W. Thermoelectric cooling--a new use for semiconductors. Schweiz Techn Z 58:733 (1961).

182. Guennoc, R. Frigatrons. Toute Electron 30:292 (1963).

183. The semiconductor as an ice machine. Funkschau 34:106 (1962).

184. Hanlein, W. Semiconductor cooling elements. Bull Schweiz Electrotechn Vereins 55:142 (1964).

185. Banaga, M. P., et al. Weak-current three-stage thermoelectric microcooler. Geliotekhnika 10:10 (1974).

186. Troyer, D. A temperature-regulated stage for the light microscope using a Peltier element. J Microsc 102:215 (1974).

187. Hughes IR Peltier cooler operates on low current. Electronic Design 9:10 (1961).

188. Salaruddin, M. A dew point hygrometer with thermoelectric cooling. Indian J Meteorol Geophys 19:341 (1968).

189. Thermoelectric modules work on low current. Electronics 37:146 (1964).

190. A very small thermoelectric device. Electronica 10:183 (1964).

191. Mamikonjan, S. V., et al. The SI/LI spectrometer cooled with the Peltier elements with resolving power of 460 eV. Jad Energ 23:461 (1977).

192. Lavan, Z., et al. Thermoelectric heat pump for residential heating and cooling. Proc Am Power Conf 39:805 (1977).

193. Anatychuk, L. I., et al. Limiting possible cooling by multicascade thermoelectric cooling. Izv Vuz Priborostr 21:116 (1978).

194. Tynan, E. E., and R. J. Von Gutfield. Microscope stage sample holder capable of temperature variation between 30 and 800 K. (For thermoelectric effect study.) Rev Sci Instrum 46:569 (1975).

195. Benedetti, P. A., and S. Grassi. Thermoelectric photocathode cooler allowing rapid interchange of end-on photomultipliers. Appl Opt 19:832 (1980).

196. Stil'bans, L. S., E. K. Iordanishvili, and T. S. Stavitskaya. Thermoelectric cooling. Izvest Akad Nauk SSSR, Ser Fiz 20:81 (1956).

197. Simons, R. E. Thermal conditioning system for an optical data link. IBM technical report TR 00.1628-1, Systems Development Div., Poughkeepsie, NY, 1970.

198. Re, R. K. Semiconductor cooling devices survey. Military Ind Sys Des 7:20 (1963).

199. Robert, L. Proportional temperature controller for thermoelectric coolers. Rev Sci Inst 34:1277 (1963).

200. Robert, L. The outlook for thermoelectric devices. Electron Ind 22:D6 (1963).

201. Robertson, J. T. The design of a miniature TE heat pump. Electronics News 7:53 (1962).

202. Poslawski, R. P. Developing a thermoelectric baffle. Electron Ind 21:106 (1962).

203. Thermoelectric vacuum baffles semiconductor elements. Electronics 33:110 (1960).

204. Kolenko, Y. A., et al. Thermoelectric photomultiplier cooling. PTE 3:140 (1959).

205. Mount, T. E., and I. K. Hughes. Peltier cooler operates on low current. Electronic Design 9:10 (1961).

206. Peltier cooling advanced. Missiles and Rockets 8:23 (1960).

207. Robertson, J. The design of a minute TE heat pump. Electronics News 7:53 (1962).

208. Meloni, A. Thermoelectric devices. Instrum and Control Systems 43:34 (1970).

209. Anatychuk, L. I., A. P. Melnik, and D. D. Nikirsa. Thermoelectric coolers for micromodules. Instrum and Experimental Techniques 20:1516 (1977).

210. Efremov, A. A. Possibility of constructing thermoelectric heat regulating systems for extracorporeal circulation apparatus. Biomed Eng 12:243 (1978).

211. Harpster, J. W., P. R. Swinehart, and F. Braun. Solid-state thin-film thermoelectric coatings. Solid-State Electronics 18:551 (1975).

212. Harpster, J. W., et al. Thermoelectric thin film thermal coating systems. NASA, final report on contract NAS8-28519, 28 Aug 1973.

213. Neuartige, H. New semiconductor cooling elements. Techn Rundschau 53:7 (1961).

214. A new thermoelement with an outer diameter of 0.34 mm. Arch Techn Messen 309:R140 (1961).

215. Neuartige, H. New semiconductor cooling elements. Electrotechn und Mashinenbau 78:460 (1961).

216. New thermorefrigerator elements with the Peltier effect. R C Composante Electron 46:7 (1963).

217. Proceedings of the Intersociety Energy Conversion Engineering Conference, Los Angeles, CA, Sept 1966. (Published by the Am Inst Aeronautics and Astronautics, New York City, NY.)

218. Azarov, A. I. A thermoelectric cooling device, Soviet Patent 332301, 1972. Available NTIS AD A008256, 12 Aug 1974.

219. Nayer, V. A., et al. Three-stage micro cooler. Khododil'naya Tekhnika 7:24 (1969). Available NTIS AD A014236, 4 Sept 1975.

220. Bohme, B. Cooling elements in reference to the Peltier effect on a semiconductor basis. Electronics 11:225 (1962).

221. Burnett, T. B., H. O. Lorch, and J. E. Thompson. Some problems in the development of a commercial thermoelectric refrigerator. Br J Appl Phys 12:595 (1961).

222. Goldsmid, H. J., and A. S. Gray. Thermoelectric refrigeration at very low temperatures. Cryogenics 19:289 (1979).

223. Hardy, W. S., and T. Rutherford. Thermoelectric apparatus for the preparation of fresh frozen tissue sections. Nature 196:785 (1962).

224. Heinecke, J. B. Design and performance of a thermoelectric refrigerator. Refrig Eng 67:34 (1959).

225. Rocklin, S. R. Thermoelectric pump. USA Patent 3,116,693, 15 May 1966.

226. Allison, D. K. Cooling micromodules internally with Peltier junctions. Electronics Reliability and Microminiaturization 1:359 (1962).

227. Kolenko, A., et al. A thermoelectric device for the measurement of liquid heat content. Soviet Patent 122900, 1959.

228. Kelly, J. C. Thermoelectric applications to industrial problems. IRE Trans Ind Elec 9:61 (1962).

229. Parrot, J. E., and A. W. Penn. Applications of the Peltier effect. AEI Eng 2:202 (1962).

230. Griffith, M. V. Thermoelectric refrigeration. Adv Sci 18:135 (1961).

231. Reich, A. D. Thermoelectric cooling system. USA Patent 3,125,860, 12 July 1962.

232. Anatychuk, L. I. Low-inertia thermoelectric microrefrigerator. Prib Tekn Eksp 15:286 (1972).

233. Mole, C. J., et al. Thermoelectric cooling technology. Paper TOD-70-63. Proc IEEE Int Semiconductor Power Converter Conf, Baltimore, MD, 12-15 May 1969.

234. Rao, K. R. (ed.). Proc Int Conf Thermoelectric Energy Conversion. The University of Texas at Arlington, Arlington, TX, 1-3 Sept 1976.

235. Kolenko, E. A., and M. G. Verdiev. Utilization of thermosiphon in thermoelectric devices. Appl Solar Energy 9:7 (1973).

236. Zeskind, D. A. Thermoelectric heat pumps cool packages electronically. Electronics 53:109 (1980).

237. Krigman, A. Applications of thermoelectric effects. Instrum and Control Systems 44:27 (1971).

238. Jepson, R. M., and G. G. Messick. Designing low-current thermoelectric coolers. Electronics 34:58 (1961).

239. Haacke, G. Electrothermal cooling appliances and their applications. Verein Deutscher Ingenieure Zeitung 103:753 (1961).

240. Bean, J. E. Applications of thermoelectric cooling. Indust Electronics 1:132 (1962).

241. Iordanishvili, E. K., and L. S. Stil'bans. Thermoelectric microrefrigerators. Zh Tekh Fiz 26:945 (1956).

242. Hanlein, W. The technological problems in the use of the Peltier effect. Kaltetechn 12:137 (1960).

243. Frantt, E. W., R. S. Lackey, and H. A. Wagner. Thermoelectric spot cooling applications. IRE Wisconsin Convention Records 3:136 (1959).

244. Design details outlined for thermoelectric unit. Electronic Design 9:6 (1961).

245. Lefferts, P. Thermoelectric cooling. Machine Design 37:118 (1965).

246. Heinicke, J. B. The design and performance of a thermoelectric refrigerator. Proc Am Soc Refrig Engrs, New Orleans, LA, Dec 1958.

247. Yamono, M., and K. Bakanti. The thermoelectric element. Japanese Patent 5779, 1962.

248. Hudspeth, W. S. What's new in cooling? Electro-Optical Systems Design 9:32 (1977).

249. Ioffe, A. F., et al. Thermoelectric cooling in refrigeration technique. Kholodil'naya Tekh 33:5 (1956).

250. Mil'Chenko, V. Y., and G. I. Lebedev. Semiautomatic unit with programmed control for checking thermoelectric thermometers. Izmer Tekh 19:84 (1976).

251. Guozi, L., and H. J. Tyrvell. The maintenance of controlled temperature differences using a thermoelectric heat pump. J Sci Instrum 41:468 (1964).

252. Ioffe, A. F. Applications of semiconductor thermopiles. Moscow: AN SSSR Press, 1951.

253. Ramert, B. A small thermoelectric thermostat. Sdelovaci Tech 11:269 (1963).

254. Bird, G. S., Jr., and A. Wamamora. The CAMBION thermoelectric hardbook. Cambridge Thermionic Corp., Cambridge, MA 02238, 1971.

255. Solid state cooling with thermoelectrics. Materials Electronic Products Corp., Trenton, NJ 08648, 1979.

256. Guide to thermoelectric heat pumps. Marlow Industries Incorp., Garland, TX 75042, 1980.

257. Standard thermoelectric modules selection guide. Borg Warner Thermoelectrics Corp., Chicago, IL 60618, 1980.

258. Simon, R. Maximum figure of merit of thermoelectric materials. Adv Energy Conversion 1:81 (1961).

259. Simon, R. Thermoelectric figure of merit of two-band semiconductors. J Appl Phys 33:1830 (1962).

260. Miller, R. C., R. R. Heikes, and A. E. Fein. Dependence of the thermoelectric figure of merit on energy bandwidth. J Appl Phys 33:1928 (1962).

261. Littman, H., and B. Davidson. Theoretical bound on the thermoelectric figure of merit from irreversible thermodynamics. J Appl Phys 32:217 (1961).

262. Littman, H. A clarification of the theoretical upper bound on the thermoelectric figure of merit derived from irreversible thermodynamics. J Appl Phys 33:2655 (1962).

263. Rittner, E. S. Comment on the theoretical bound on the thermoelectric figure of merit from irreversible thermodynamics. J Appl Phys 33:2654 (1962).

264. Donahoe, F. J. Theoretical bound on the theoretical figure of merit. Elec Engr 79:488 (1960).

265. Testardi, L. R. Calculations of the thermoelectric parameters and the maximum figure of merit for acoustical scattering. J Appl Phys 32:1978 (1961).

266. Bowley, A. E., et al. Measurement of the figure of merit of a thermoelectric material. J Sci Instrum 38:433 (1961).

267. Heylen, A. E. Figure of merit determination of thermo-electric modules. Energy Conversion 15:65 (1975).

268. Myers, W. C., and R. T. Bate. Note on measurement of figure of merit of thermoelectric materials. Rev Sci Instrum 31:464 (1960).

269. Nettelbladt, H. Measurement of figure of merit for thermoelectric materials. Zh Elteknik 6:13 (1963).

270. Lougher, E. H. Measurements of the parameters in the thermoelectric figure of merit. Elec Eng 79:358 (1960).

271. Stratton, R. The figure of merit of a thermoelectric generator. J Electronics and Control 7:73 (1959).

272. Ure, R. W. Effect of impurity scattering on the figure of merit of thermoelectric materials. J Appl Phys 30:1922 (1959).

273. Epstein, A. S. Thermoelectric figure of merit in silver selenide powders. J Appl Phys 34:3587 (1963).

274. Chasmar, R. P., and R. Stratton. The thermoelectric generators. J Electronics and Control 7:52 (1959).

275. Butyrskii, V. I., and R. V. Koval'skii. Method of measuring the figure of merit of semiconducting materials for thermoelectric devices. Soviet Patent 259213, 1970.

276. Crawford, G. J. Note on the measurement of the figure of merit of thermoelectric materials and refrigerating junctions. Rev Sci Instrum 32:353 (1961).

277. Saunders, G. A., et al. Electrical properties of arsenic-antimony alloys. Phys and Chem of Solids 26:533 (1965).

278. Shtenbek, M., and P. I. Baranskii. Methods for the precise measurement of Peltier effect and thermoelectromotive force. Zh Tekh Fiz 26:1373 (1956).

279. Fuschillo, N., and F. J. Donahoe. Adiabatic method for determining the thermal conductivity and thermoelectric figure of merit of semiconductors. Adv Energy Conversion 2:133 (1962).

280. Goldsmid, H. J. The electrical conductivity and thermoelectric power of bismuth telluride. Phys Soc Proc 71:633 (1958).

281. Katilene, E. R., and A. R. Regel. Electrical conductivity of thallium-telluride in the solid and liquid states. Soviet Physics--Solid State 6:2284 (1965).

282. Harman, T. C. Special techniques for measurement of thermoelectric properties. J Appl Phys 29:1373 (1958).

283. Harman, T. C., J. H. Cahn, and M. J. Logan. Measurement of thermal conductivity by utilization of the Peltier effect. J Appl Phys 30:1351 (1959).

284. Gramberg, G., and H. G. Plust. Electric and thermoelectric properties of the system $(Bi_{x-x\ell}Sb_{2-x\ell}Te_{x\ell})(Te_ySe_{3-y})$. Helv Phys Acta 36:237 (1963).

285. Walker, P. A. The thermal conductivity and thermoelectrical power of bismuth telluride at low temperatures. Phys Soc Proc 76:113 (1960).

286. Jain, A. L. Temperature dependence of the electrical properties of bismuth-antimony alloys. Phys Rev 114:1 (1959).

287. Moizhes, B. Y. The influence of the temperature dependence of physical parameters on the efficiency of thermoelectric generators and refrigerators. Fiziki Tverdogo Tela 2:728 (1960).

288. Hasimoto, K. Electrical properties of bismuth selenide--thermoelectric power and thermal conductivity. Mem Fac Sci, Kyushu Univ B2:187 (1958).

289. Beer, A. C. Effects of various impurities on lattice thermal conductivity in bismuth telluride. Final report, Battelle Memorial Institute, Columbus, OH. Available NTIS AD 274717, 30 Apr 1962.

290. Goldsmid, H. J. The thermal conductivity of bismuth telluride. Proc Phys Soc 69B:203 (1956).

291. McNeill, D. J. Measurement of thermal conductivity using the Peltier effect. Br J Appl Phys 14:113 (1963).

292. Tye, R. P. Thermal conductivity. New York: Academic Press, 1969.

293. Drabble, J. R., and H. J. Goldsmid. Thermal conduction in semiconductors. London: Pergamon Press, 1961.

294. Protopopescu, M., S. Zamirca, and N. Petrescu. Determinarea caracteristicilor frigoelementelordin dliaje semiconductoare cu baza de telur--studiisi cercetari metalurgie. Acad RPR 8:255 (1963).

295. Rodot, H., and M. G. Weill. Temperature variation of the thermoelectric properties of solid solutions of Bi_2Te_3 and Sb_2Te_3. J Phys et Radium 21:502 (1960).

296. Emel'yahenko, O. V., and F. P. Kesamanly. Method for rapid precision measurements of the thermoelectric power of semiconductors. Fiziki Tverdogo Tela 2:1494 (1960).

297. Herinckx, C., G. R. Offergeld, and J. L. Van Cakenberghe. Thermoelectric materials. USA Patent 3,076,859, 10 July 1961.

298. Ainsworth, L. Single-crystal bismuth telluride. Proc Phys Soc 69B:606 (1956).

299. Benel, H. The thermoelectric properties of antimony telluride and the solid solutions of Sb_2Te_3 and Bi_2Te_3. C R Acad Sci 247:584 (1958).

300. Bolling, G. F. Some thermal data for Bi_2Te_3. J Chem Phys 33:305 (1960).

301. Cluley, H. J., and P. M. Proffitt. The analysis of bismuth telluride and related thermoelectric materials. Analyst 85:815 (1960).

302. Borisova, L. A., et al. The phase diagram of the system thallium telluride-bismuth telluride and the properties of certain of its alloys. Dokl Akad Nauk SSSR 149:117 (1963).

303. Hall, R. N. An analysis of the performance of thermoelectric devices made from long lifetime semiconductors. Solid-State Electronics 2:115 (1961).

304. MacPhee, C. A. The development of thermoelectric materials for refrigeration. Can Elec Eng 5:36 (1961).

305. Beckman, O., and P. Bergvall. Doping properties of $Bi_2Te_{2.7}Se_{0.3}$. Arkiv fuer Physik 24:113 (1963).

306. Benel, H. Thermoelectric properties of antimony telluride and solid solutions of Se_2Te_3-Bi_2Te_3. Acad Sci--C R Hebdomadaires des Seances 247:584 (1958).

307. Bennett, L. C., and J. R. Wiese. Effects of doping additions on the thermoelectric properties of the intrinsic semiconductor $Bi_2Te_{2.1}Se_{0.9}$. J Appl Phys 32:562 (1961).

308. Bergvall, P., and O. Beckman. Thermoelectric properties of nonstoichiometric bismuth-antimony-telluride alloys. Solid-State Electronics 6:133 (1963).

309. Harman, T. C., et al. Preparation and some physical properties of Bi_2Te_3, Sb_2Te_3, and As_2Te_3. Phys and Chem of Solids 2:181 (1957).

310. Conn, J. B. Thermoelectric materials. USA Patent 3,055,962, 25 Nov 1960.

311. Petrescu, N., M. Protopopescu, and D. Drimmer. The high quality purification of tellurium. Rev Roumaine Metallurgy 5:227 (1960).

312. Butenko, V. I. Apparatus for study of thermoelectric properties of metals. Ind Lab 42:75 (1976).

313. Kokosh, G. V., and S. S. Sinani. The effect of impurities on the thermoelectric properties of a Sb_2Te_3 - Bi_2Te_3 solid solution. Fiziki Tverdogo Tela Sbornik 1:89 (1959).

314. Kokosh, G. V., and S. S. Sinani. Thermoelectric properties of alloys of the pseudobinary system Sb_2Te_3 - Bi_2Te_3. Fiziki Tverdogo Tela Sbornik 2:1118 (1960).

315. Konorov, P. P. Electrical properties of bismuth chalcogens. Soviet Phys 1:1365 (1956).

316. Gordyakova, G. N., et al. A study of the thermoelectric properties of solid solutions of bismuth telluride and bismuth selenide. Zh Tekh Fiz 28:3 (1958).

317. Gordyakova, G. N., and S. S. Sinani. Thermoelectric properties of bismuth telluride with alloying additives. Soviet Phy 3:908 (1958).

318. Yim, W. M., and A. Smith. Bi-Sb alloys for magneto-thermoelectric and thermomagnetic cooling. Solid-State Electronics 15:1141 (1972).

319. Myers, W. C., and R. T. Bate. Thermoelectric properties of Bi_2Te_3 - Bi_2Se_3 alloys. Am Phys Soc Bull 4:409 (1959).

320. Quenault, A. M. Thermoelectricity in the intermediate state. Phil Mag 9:331 (1964).

321. Rosi, F. D., B. Abeles, and R. V. Jensen. Materials for thermoelectric refrigeration. Phys and Chem of Solids 10:191 (1959).

322. George, W. R., et al. The sintering of bismuth telluride. Phys Soc Proc 74:768 (1959).

323. Goletskaya, A. D., et al. Production and investigation of thermoelectric materials on the Bi - Sb - Te basis. Fiziki Tverdogo Tela 3:3002 (1961).

324. Hach, R. J., M. J. Brau, and T. S. Burkhalter. Continuous casting of thermoelectric materials. Rev Sci Instrum 32:1341 (1961).

325. Harman, T. C., S. E. Miller, and H. L. Goering. Preparation and electrical properties of Bi_2Te_3. Semiconductor Abstracts 3:713 (1955).

326. Etori, K. Transient behavior of thermoelectric cooling with Bi_2Te_3 compound semiconductors in atmosphere. Trans Soc Instrum Control Engrs 5:103 (1969).

327. Goldsmid, H. J., and A. R. Sheard. Preparation of material for thermocouples. USA Patent 3,017,446, 16 Dec 1957.

328. Landecker, K. Some further remarks on the improvement of Peltier junctions for thermoelectric cooling. Energy Conversion 14:21 (1974).

329. Beverly, V. H. Method and materials for obtaining low resistance bonds to bismuth telluride. USA Patent 3,017,693, 1963.

330. Goldsmid, H. J., A. R. Sheard, and D. A. Wright. The performance of bismuth telluride thermojunctions. Br J Appl Phys 9:365 (1958).

331. Bowers, R., et al. InAs and InSb as thermoelectric materials. J Appl Phys 30:930 (1959).

332. Ertl, M. E., G. R. Pfister, and H. J. Goldsmid. Size dependence of the magneto Seebeck effect in bismuth antimony alloys. Br J Appl Phys 14:161 (1963).

333. Taylor, P. F., and C. Wood. Thermoelectric properties of silver telluride. J Appl Phys 32:1 (1961).

334. Rupprecht, J. Bi_2Te_3 - Sb_2Te_3 alloys with added tellurium and selenium. Z Naturforsch 17A:628 (1962).

335. Teramoto, I., and S. Takayanagi. Relation between the electronic properties and the chemical bonding of $Sb_xBi_{2-x}Te_{3-y}Se_y$ system. Phys and Chem of Solids 9:124 (1961).

336. Haase, D. J., and H. Steinfink. Thermoelectric and electrical measurements in the Er-Se system. J Appl Phys 36:3490 (1965).

337. Rittner, E. S., and G. F. Neumark. Theoretical bound on the thermoelectric figure of merit of two-band semiconductors. J Appl Phys 34:2071 (1963).

338. Ramsey, T. H., H. Steinfink, and E. J. Weiss. Thermoelectric and electrical measurements in the La-Te system. J Appl Phys 36:548 (1965).

339. Schwartz, R. J. Thermoelectric and galvanomagnetic measurements on $(Bi_2Te_3)_5$ - $(Bi_2Se_3)_1$ - $(Sb_2Te_3)_{18}$. J Appl Phys 38:2865 (1967).

340. Haase, D. J., and H. Steinfink. Thermoelectric and electrical measurements in the erbium-tellurium system. J Appl Phys 37:2246 (1966).

341. Cortes, C. M., and R. G. Hunsperger. Effects of contact resistance and dopant concentration in metal-semiconductor thermoelectric coolers. IEEE Trans Elec Dev ED-27:521 (1980).

342. Birkholz, U., and G. Haacke. Influence of halid doping on the thermoelectric properties of the system $Bi_2Te_{3-x}Se_x$. Z Naturforsch 17A:161 (1962).

343. Gitsu, D. V., et al. On the thermoelectromotive force in bismuth and bismuth-tellurium alloys. Fiziki Tverdogo Tela 4:22 (1962).

344. Khombaty, M. B., et al. Studies on bismuth telluride based semiconductors for thermoelectric cooling. Indian J Pure and Appl Phys 2:398 (1964).

345. Rodot, M., H. Rodot, and R. Triboulet. Some properties of mercury selenide - mercury telluride solid solutions. J Appl Phys 32:2254 (1961).

346. Airapetiants, S. V., et al. On the mobility of electrons and holes in solid solutions based on lead and bismuth tellurides. Zh Tekhn Fiz 27:2009 (1957).

347. Wright, D. A. Bismuth telluride and related compounds. Res 12:300 (1959).

348. Borisova, L. A., et al. Properties of thallium-bismuth-tellurium alloys. Russian J Inorg Chem 8:1415 (1963).

349. Stambaugh, E. P., et al. Development of improved thermoelectric materials for spacecraft. Final report, NASA Contract NAS8-11452, 25 June 1965.

350. Appel, J. Theory of thermoelectric and thermomagnetic effects in nonpolar isotropic semiconductors. Phys and Chem of Solids 8:353 (1959).

351. Kaganov, M. A., et al. On the measurement of thermoelectric properties of semiconductors. Fiziki Tverdogo Tela 1:988 (1959).

352. Harman, T. C. Measurement of thermoelectric materials and devices. Semiconductor Products 6:13 (1963).

353. Ure, R. W. Theory of materials for thermoelectric and thermomagnetic devices. Proc IEEE 51:699 (1963).

354. Emelyanenko, O., et al. Thermoelectric power of strongly compensated n-type GaAs. Soviet Physics--Semiconductors 4:1913 (1971).

355. Cortes, C. M., and R. G. Hunsperger. Effects of contact resistance and dopant concentration in metal-semiconductor coolers. IEEE Trans, Electron Devices ED27:521 (1980).

356. Krolick, C. F. Thermoelectricity: Report on the state-of-the-art materials. MEL report 205/64, US Navy, Marine Engineering Lab., Annapolis, MD, 1964.

357. Shilliday, T. S. Performance of composite Peltier junctions of bismuth telluride. J Appl Phys 28:1035 (1957).

358. Klemens, P. G. Theoretical requirements for thermoelectric materials. Thermoelectricity quarterly progress report number 1, US Navy Bureau of Ships (contract NOBS-84687, Westinghouse Research Labs), Aug 1962.

359. Domenicali, C. A. Thermoelectric power and electron scattering in metal alloys. Phys Rev 112:1863 (1958).

360. Bridgman, P. W. The thermodynamics of electrical phenomena in metals. New York: Macmillan, 1934.

361. Herinckx, C., and A. Monfils. Electrical determination of the thermal parameters of semiconducting thermoelements. Br J Appl Phys 10:235 (1959).

362. Huneidi, F. Criteria for selecting thermoelement materials for thermoelectric Peltier devices. ASHRAE J 5:80 (1963).

363. Smith, G. E., and R. Wolfe. Thermoelectric properties of bismuthantimony alloys. J Appl Phys 33:841 (1962).

364. Schwartz, R. J. Thermoelectric and galvanometric measurements on $(Bi_2Te_3)_5(Bi_2Se_3)(Sb_2Te_3)_{18}$. J Appl Phys 38:2865 (1967).

365. Ure, R. W., and R. R. Heikes. Materials requirements for segmented thermoelectric materials. Adv Energy Conversion 2:231 (1962).

366. Smirous, K., and L. Stourae. Firm solutions of Bi_2Te_3 and Sb_2Te_3 as p-conducting materials for semiconductor thermoelectric cooling. Z Naturforsch 14A:848 (1959).

367. Streedhar, A. K., et al. Development of semiconductor materials for thermoelectric cooling. J Inst Telecom Engrs 10:207 (1964).

368. Stourac, L. Influence of aging on change in electrical properties of semiconducting systems of Bi_2Te_3 and Bi_2Se_3. Czech J Phys 9:717 (1959).

369. Thermoelectric materials in alloy of bismuth telluride. Electronic Design 9:25 (1961).

370. Wolfe, R., and H. Wernick. Thermoelectric devices and material. Bell Lab Rec 40:190 (1962).

371. Alatyrtsev, G. A., and Y. N. Malevskig. The connection of thermoelectric elements on the base. Moscow: AN SSSR Press, 1961.

372. Champness, C. H., P. T. Chiang, and P. Parekh. Thermoelectric properties of bismuth telluride - antimony telluride alloys. Can J Phys 43:653 (1965).

373. Cowles, L. E., and L. A. Dauncey. Apparatus for the rapid scanning of the Seebeck coefficient of semiconductors. J Sci Instrum 39:16 (1962).

374. Dennis, J. H. Anisotropy of the Seebeck coefficients of bismuth telluride. Adv Energy Conversion 1:99 (1961).

375. Rittner, E. S. On the theory of the Peltier heat pump. J Appl Phys 30:702 (1959).

376. Silvestri, M., and P. Lucardesi. Peltier effect. Elettrificazione 2:65 (1976).

377. Jean, R., and R. Liot. Drawbacks in the Peltier effect. Vide 17:186 (1962).

378. Haenlein, W. Technologie and anwendung des Peltier effektes. Zh Instrumentenk 72:347 (1964).

379. Pritchard, W. M. The coefficient of performance of thermoelectric cooling devices. Proc IEEE 52:442 (1964).

380. Connor, R. J., et al. Martin thermal analysis system version 1.0. Final report MDS-SPLPD-71-FD238, Martin Marietta Corp., Denver, CO, June 1971.

381. Moore, R. G. Exact computer solution of segmented thermoelectric devices. Adv Energy Conversion 2:183 (1962).

382. Private communication with Dr. S. Nunneley and Dr. L. Myhre, Crew Protection Branch (VNB), USAFSAM, Brooks AFB, TX.

383. Adolph, E. F., et al. Physiology of man in the desert. New York: Hafner Publishing Company, 1969.

384. Kolenko, Y. A., A. G. Tauber, and A. G. Shcherbina. Coupling the stages in a multi-stage thermoelectric pile. Soviet Patent 123215, 1959.

385. McAdams, W. H. Heat transmission. New York: McGraw-Hill, 1954.

386. Marlow, R., and P. B. Click. Estimating heat loads on multistage thermoelectric heat pumps. Proc Soc Photo-Optic Instrum Engrs 116:94 (1977).

387. Pitts, D. R., and L. E. Sissom. Heat transfer. New York: McGraw-Hill, 1977.

388. Kutateladze, S. S. Fundamentals of heat exchange theory. Moscow: Izd-vo Nauka, 1970.

389. Jakob, M. Heat transfer. New York: John Wiley and Sons, 1958.

390. Gryadunov, A. I., and D. Mamatisakov. Quadratic form of generalized thermoelectric converter surface heat balance equations. Geliotekhnika 14:19 (1978).

391. Watson, P. C. Graphical methods of solving thermoelectric pump problems. Electo-Technol 71:74 (1963).

392. Kozlyuk, V. N., and G. M. Shchegolev. Thermodynamic analysis of permeable thermoelectric refrigerators. Heat Transfer - Soviet Res 7:116 (1975).

393. Kazanov, M. A., and A. S. Rivkin. Synthesis of a prescribed temperature-time process by means of semiconductor-type thermoelectric cells. J Eng Phys 24:641 (1973).

394. Gukhman, A. A. The physical bases of heat transfer. Moscow: Energoizdat Press, 1934.

395. Dul'nev, G. N. Heat transfer in radioelectronic devices. Moscow: Gosenergoizdat Press, 1963.

396. Mikheyev, M. A. The fundamentals of heat transfer. Moscow: Gosenergoizdat Press, 1956.

397. Ramadan, A. M. Heat transfer intensification in thermoelectric cooling devices. PhD Dissertation, Leningrad Teknol Inst Kholod Promyshl, 1963.

398. Brandstetter, A., and E. P. Chock. Generalized analysis of thermoelectric device configurations. Energy Conversion 16:125 (1977).

399. Ybarrondo, L. J. The effect of finite hot and finite cold junction fins on the performance of a thermoelectric heat pump. Solid-State Electronics 6:357 (1963).

400. Zito, R. Dynamic behavior of a thermoelectric heat pump. Electro-Technol 71:64 (1963).

401. Gabrielli, I. Optimization of multistage Peltier cooling systems. Proc Second Int Conf Thermoelec Energy Conversion, Arlington, TX, 22-24 Mar 1978.

402. Kaganov, M. A. Optimum construction of semiconductor coolers of liquid flows. J Eng Phys 15:309 (1968).

403. Siegel, R., and J. R. Howell. Thermal radiation heat transfer. New York: McGraw-Hill, 1972.

404. Grosby, C. R., M. H. Norwood, and B. R. West. The effects of heat transfer on optimum Peltier heat-pumping. Am Soc Mech HT-11:7 (1962).

405. Anatychuk, L. I., et al. Construction of thermoelectric refrigerators with limited heat sink. Izv Vuz Priborostr 19:113 (1976).

406. Marlow, R. Estimating heat loads for thermoelectric coolers. Electro-Optic Systems Design 9:86 (1977).

407. Ioffe, A. F., B. Y. Moyzhes, and L. S. Stil'bans. Concerning power applications of thermoelements. FFT 2:11 (1960).

408. Spring, K. H. Direct generation of electricity. New York: Academic Press, 1965.

409. Okhotin, A. S., et al. Thermoelectric generators. Moscow: Atomizdat Publishers, 1976.

410. Lidorenko, N. S., et al. Thermoelectric batteries of increased effectiveness. Izv Energetika i Transport 4:117 (1972). Available NTIS AD 759239, 3 Apr 1973.

411. Elfvinf, T. M. Study of design problems and mode of operation for thermoelectric refrigerators. ASHRAE J 5:69 (1963).

412. Byalel'dinov, M. F., et al. Semiconductor thermoelectric batteries for air conditioning. Kholodil'naya Tekhnika 7:20 (1973). Available NTIS AD A005209, 20 Feb 1975.

413. Miller, R. C., and R. W. Ure. Thermoelectric generator materials. Proc ARS Space Power Systems Conf, Santa Monica, CA, 26-30 Sept 1960.

414. Kotyrlo, G. K., and G. M. Shchegolev. Thermal diagrams of thermoelectrical devices. Translation FTD-HC-23-1567-74, Foreign Technology Division, Wright-Patterson AFB, OH. Available NTIS AD 787420, 31 Oct 1974.

415. Manasyan, Y. G. Marine thermoelectric devices and installations, Moscow: Sudostroyeniye Press, 1968. Available NTIS AD 715457, 7 Dec 1970.

416. Pomazanov, I. N., and P. L. Tikhomirov. Semiconductor thermal pump based on the principle of combined use of thermoelectric effects. Izv Leningradskogo Elektrotekhnicheskogo Inst, 51:94 (1963). Available NTIS AD 612370, 22 Mar 1965.

417. Graham, R. W. Rechargeable batteries--advances since 1977. NJ: Noyes Data Corp., 1980.

418. Birk, J. R., K. Klunder, and J. C. Smith. Superbatteries: A progress report. IEEE Spectrum 16:49 (1979).

419. Lyman, J. Battery technology--packing more muscle into less space. Electronics 48:75 (1975).

420. Yates, W. Batteries: Cordless power. Electronic Products 21:39 (1978).

421. Bak, D. J. Long-life battery provides onboard protection of volatile memories. Design News 9:76 (1978).

422. Despite their vulnerability, batteries are still reaching new market highs. Electronics Design News 22:26 (1977).

423. Wentink, R. F., and I. Weinstock. Understanding sealed lead acids lets you apply them effectively. Electronics Design News 23:53 (1978).

424. Gilder, J. H. In power, longevity and voltage, batteries are reaching new peaks. Electronic Design 22:28 (1974).

425. Grossman, M. Focus on batteries. Electronic Design 26:88 (1978).

426. Hair, G. Profiling battery performance. Electronic Products 23:44 (1980).

427. Pensabene, S. F. The truth about Ni-Cd cell reversal. Machine Design 48:97 (1976).

428. Stakem, D. Inside lithium batteries. Electronic Products 22:75 (1979).

429. Dry cell report. Machine Design 45:137 (1973).

430. Strauss, H. J. Battery uses and special cells. In M. Kaufman and A. H. Seidman (eds.). Handbook of electronics calculations. New York: McGraw-Hill, 1979.

SUPPLEMENTARY REFERENCES

Aliev, S. Thermal conductivity and thermoelectric power of GaAs at low temperatures. Phys Rev 138:A1270 (1965).

Antonov, Y. I., et al. Ustroystva dlya okhlazhdeniya primiyemnikov izlucheniya. Moscow: Machine Building Press, 1969.

Babin, V. P., and E. K. Iordanishvili. Effect of switching-layer resistance on transient thermoelectric cooling. Soviet Physics-Technical Physics 17:184 (1972).

Blatt, F. J. Theory of mobility of electrons in solids. In F. Seitz and D. Turnbull (eds.). Solid-State Physics, Vol. 4, New York: Academic Press, 1957.

Boltaks, B. I. Semiconductors in science and technology. Moscow: Akad Nauk SSSR, 1957.

Birkholz, U. Charts for construction and operation of thermoelectric cooling devices. Kaltetechn 13:335 (1961).

Brooks, H. Advances in electronics and electron physics. New York: Academic Press, 1955.

Bullis, W. M. Minority carrier thermoelectric cooling. J Appl Phys 34:1648 (1963).

Burshtein, A. I. On the economy of cascade cooling thermogenerators. Fiziki Teverdogo Tela 2:2505 (1960).

Chambers, R. G. The two-based effect in conduction. Proc Phys Soc (London), section A, 65:903 (1952).

Darken, L. S., and R. W. Gurry. Physical chemistry of metals. New York: McGraw-Hill, 1953.

DeGroot, S. R. Thermodynamics of irreversible processes. New York: Interscience, 1952.

Denbigh, K. G. The thermodynamics of the steady state. London: Methuen and Company Limited, 1951.

Dike, P. H. Thermoelectric thermometry. Philadelphia: Leeds and Northrup, 1954.

Dunlop, W. C. An introduction to semiconductors. New York: John Wiley and Sons, 1957.

Fischer, J. D. Solid-state environmental control system. Final report MKP-306, USA Mobility Equipment Research and Development Center, Fort Belvoir, VA. Available NTIS AD 771154, Sept 1973.

Frank, L. E., and P. E. Taylor. On the mechanical testing of thermoelectric modules. Adv Energy Conversion 4:128 (1964).

Fuller, C. S. Semiconductors. New York: Reinhold, 1959.

Gambeno, R. J., W. D. Grobman, and A. M. Toxen. Anomalously large thermoelectric cooling figure of merit in the Kondo systems $CePd_3$ and $CeLn_3$. Appl Phys Letters 22:506 (1973).

Gatos, H. C. Properties of elemental and compound semiconductors. New York: Interscience Publishers, 1960.

Gorbachev, V. V., et al. Cooling in semiconductors by exclusion. Radiotekh and Elektron 17:1670 (1972).

Guazzoni, G. E. Characterizing thermoelectric generators. Instrum and Control Systems 45:85 (1972).

Hare, G. E. Technical summary of patents on thermoelectric devices. Report AERE-M1531, Applied Physics Group, United Kingdom Atomic Energy Authority Research Group, Atomic Energy Research Establishment, Harwell, Berkshire, England, Jan 1965.

Harman, T. C., and J. M. Honig. Theory of galvano-thermomagnetic energy conversion devices for refrigerators and heat pumps. J Appl Phys 33:3188 (1962).

Hendricks, T. J., and R. J. Buist. A study of thermoelectric design criteria for maximizing cool-down speed. Proc Third Int Conf Thermoelec Energy Conversion, Arlington, TX, 12-14 Mar 1980.

Herring, C. Transport properties of a many-valley semiconductor. Bell Systems Tech J 34:237 (1955).

Holton, H., P. Masur, and S. R. DeGroot. On the theory of thermocouples and thermocells. Physica 19:1109 (1953).

Horvay, I. B. Thermoelectric transients. IEEE Trans Appl Ind 66:111 (1963).

Hoyos, G. E., et al. Numerical analysis of transient behavior of thermoelectric coolers. Energy Conversion 17:23 (1977).

Idnurm, M., and K. Landecker. Experiments with Peltier junctions pulsed with high transient currents. J Appl Phys 34:1806 (1963).

Iordanishvili, E. K., and B. E. Malkovich. Experimental study of transient thermoelectric cooling. J Eng Phys 23:1158 (1972).

Ivanova, K. F., et al. Control of a nonstationary process of thermoelectric cooling by variation of the geometric shape of the branches of a thermoelement. Inzh-Fiz Zh 32:474 (1977).

Jaklovazky, J., and G. H. Aldica. Peltier effect thermostating in electronics. Electrotech Electron and Autom and Electron 23:17 (1979).

Jarusek, J. Information on the time constant of thermoelectric and resistance thermometers. Mereni A Regulace 24:128 (1976).

Kireev, P. S. Semiconductor physics. Moscow: Vysshaya Shkola Publishers, 1974.

Kotyrlo, G. K., and G. M. Shchegolev. Effect of temperature profile in a permeable thermoelectric refrigerating battery on its energetic characteristics. J Eng Phys 22:122 (1972).

Kozlyuk, V. N., and G. M. Shchegolev. Thermodynamic analysis of permeable thermoelectric refrigerators. Teplofiz and Teplotekh 25:96 (1973).

Landecker, K. Heat transport in coaxial thermoelectric disks with radial flow of current. J Appl Phys 49:4942 (1978).

LeClaire, A. D. Progress in metal physics. London: Pergamon Press, 1953.

Melehy, M. A. Theory of minority carrier thermoelectric cooling. J Appl Phys 33:2100 (1962).

Naer, V. A., et al. Thermoelectric cascade-type microrefrigerators. Appl Solar Energy 9:61 (1973).

Nasby, R. D., and E. L. Burgers (eds.). Proc 7th Intersociety Energy Conversion Eng Conf, San Diego, CA, 1972.

Neild, A. B. Problem areas and experiences with thermoelectric equipment. SAE Trans 71:102 (1963).

Okhotin, A. S., et al. Methods for measuring characteristics of thermoelectric materials and converters. Moscow: Nauka Publishers, 1974.

Okhotin, A. S., et al. Thermophysical properties of semiconductors. Moscow: Atomizdat Publishers, 1972.

Poslt, Z. Graphical methods of designing thermoelectric cooling devices. Tesla Electronics 1:27 (1968).

Power, M., and R. A. Handelsmann. Generalized calculation of thermoelectric efficiency. Adv Energy Conversion 1:45 (1961).

Reich, A. D., and J. R. Madigan. Transient response of a thermocouple circuit under steady currents. J Appl Phys 32:294 (1961).

Reich, A. D., T. Arai, and J. R. Madigan. Transient effects in Peltier Coolers. J Appl Phys 32:2493 (1961).

Reitz, J. R. Solid state physics. New York: Academic Press, 1955.

Rupprecht, J., and R. G. Marer. Neuere untersuchungen an halbleitenden mischkristallen unter besonderer berucksichtigung von zustandsdiagrammen. Physica Status Solidi 8:3 (1965).

Schreiner, H., and F. Wendler. Recrystallization and grain growth in the sintering process, particularly in sintered thermoelectric materials from bismuth telluride and antimony-bismuth telluride. Zh Metallk 17:684 (1963).

Schreiner, H., and F. Wendler. Sintering theory and effects in the powder metallurgy of thermoelectric materials. Zh Metallk 15:218 (1961).

Seiler, M. R., and T. S. Shilliday. Reliability factors in thermoelectric generator design. Proc IRE 49:1952 (1961).

Seitz, F. Modern theory of solids. New York: McGraw-Hill, 1940.

Sheard, A. R. Comparison of zone melted and sintered materials for thermoelectric refrigeration devices. J Electronics and Control 13:253 (1962).

Shelpuk, B. Thermoelectric air conditioner performance improvement investigation. Final report AFAPL-TR-69-69, USAF Aero Propulsion Laboratory, Wright-Patterson AFB, OH. Available NTIS AD 864745, Oct 1969.

Shockley, W. Electrons and holes in semiconductors. New York: Van Nostrand, 1950.

Skuratovskiy, N. O., and V. F. Mikheyev. Comparative evaluation of methods of measurement of active resistance of thermoelectric heating and cooling devices. Geliotekhnika 5:67 (1970). Available NTIS AD 762324, 2 July 1973.

Smith, R. A. Semiconductors. London: Cambridge University Press, 1959.

Smythe, W. R. Static and dynamic electricity. New York: McGraw-Hill, 1939.

Spenke, E. Electric Semiconductors. New York: McGraw-Hill, 1958.

Stefanakos, E. K., A. Abul-Fadl, and M. D. Workman. Measurements of Peltier cooling at a Ga-GaAs interface using a liquid-phase epitaxy system. J Appl Phys 46:3002 (1975).

Tomescu, F. M. Operating ranges of thermoelectric devices. Rev Roum Sci Tech Ser Electrotech and Energ 22:227 (1977).

Ure, R. W. Thermoelectric effects in nonlinear junctions. J Appl Phys 33:1902 (1962).

Van der Ziel, A. Solid-state physical electronics. Englewood Cliffs, NJ: Prentice-Hall, 1976.

Wilson, A. H. Theory of metals. New York: Cambridge University Press, 1953.

Wolfe, R., and E. T. Doherty. Holographic interferometry of the distortion of thermoelectric cooling modules. J Appl Phys 37:5008 (1966).

Zuikker, F. Physical properties of solid materials. New York: Interscience, 1954.

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

A	surface area
α	Seebeck coefficient
Ag	silver
Ah	ampere-hours
As	arsenic
Ba	barium
Bi	bismuth
b	heat transfer coefficient
β	heat exchanger fin factor
BTU	British thermal unit
Calorie	kilogram-calorie
calorie	gram-calorie
Ce	cerium
Cu	copper
°C	degrees Centigrade
cm	centimeter
cm^2	centimeter squared
cm^3	centimeter cubed
CW	chemical warfare
δ	electrical conductivity
$\frac{df(x)}{dx}$	first derivative [of a function f(x)] with respect to x
ΔT	temperature difference
ΔV	voltage difference
E_g	band-gap energy of a semiconductor
n	efficiency
°F	degrees Fahrenheit
ft^2	foot squared
g	gram
Ge	germanium
hr	hour
I	electrical current
In	indium
in.	inch

$in.^2$	inch squared
$in.^3$	inch cubed
k	thermal conductivity
°K	degrees Kelvin
KR	product of net thermal conductivity and net electrical conductivity
ℓ	length
m	substitution variable used to simplify a complex mathematical expression
m	meter
m^2	meter squared
m^3	meter cubed
mAh	millampere-hours
MITAS	Martin Marietta thermal analysis computer program
Mn	manganese
μV	microvolt
N	number of thermoelectric couples
ν	shape ratio variable (area to length)
N_c	free charge carrier density
n-type	semiconductor with an excess electron concentration
O	oxygen
ω	substitution variable used to simplify a complex mathematical expression
ohm	unit of electrical resistance
P	electrical power
P	phosphorous
Φ	thermoelectric coefficient of performance

Pb	lead
P_e	net Joule heat of a thermoelectric cooling system
p-type	semiconductor with an excess hole concentration
Q_a	heat to be absorbed by the cold junction of a thermoelectric cooling system
Q_c	heat flow into a thermoelectric cold junction
Q_d	heat to be dissipated by a thermoelectric cooling system
Q_e	environmental heat leakage absorbed by a subject dressed in CW protective clothing
Q_F	Fourier heat
Q_h	heat flow from a thermoelectric hot junction
Q_J	Joule heat
Q_m	metabolic heat
Q_P	Peltier heat
Q_T	Thomson heat
R	net electrical resistance
ρ	resistivity
S	sulfur
Sb	antimony
Se	selenium
Si	silicon
T	absolute temperature
τ	Thomson coefficient
(T)	functional temperature dependence
$\overline{T}$	average absolute temperature
T_a	temperature of the ambient air external to a CW protective ensemble

T_c	temperature of a thermoelectric cold junction
T_e	tellurium
T_h	temperature of a thermoelectric hot junction
T_i	human temperature (oral)
T_s	temperature of the air inside a CW protective ensemble
V	voltage
V_o	operating power supply voltage
W	watts
x	position
Z	thermoelectric figure of merit
Zn	zinc