DEVELOPMENT OF MINIATURE PERSONAL THERMOELECTRIC GENERATOR

by

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A thesis submitted in fulfillment of the requirements for the degree of

MASTERS OF ENGINEERING MECHANICAL

DUBLIN CITY UNIVERSITY

September 2004

Approved by ______________________________
Chairperson of Supervisory Committee

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DECLARATION

I hereby certify that this material, which I submit for assessment on the programme of study leading to the award of Master in Mechanical Engineering (M.Eng) is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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DEVELOPMENT OF MINIATURE PERSONAL THERMOELECTIC GENERATOR

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A. ABSTRACT

This paper outlines research toward the degree of Masters in Engineering (M.Eng) in the Department of Mechanical Engineering at Dublin City University. The thesis focuses on experimental and analytical investigations on the dynamics of thermocouples and thermopiles reaction to low temperature (less than 400°C or waste heat) for the feasibility and purpose of generating electricity. Thermocouples generate unique voltages at relative set temperatures. It is with this voltage that the development applications of conductive heat flow and radiation in waste heat electrogeneration for miniature personal thermoelectric generation is considered.

The process involves a thermal heat source (the body) extracting the necessary power between the temperature differences into electrical power. Both passive and active properties of this thermal generator are investigated by measuring the mechanical and electrical properties of the couples and piles and the electro motive force produced during this electrogeneration process.

The thesis work consists of the design, construction, processing and analyzing to understand the process and characterization of the device for application.

***There are* many devices in a man's heart; nevertheless the counsel of the LORD, that shall stand. -Proverbs 19:21**

B. ACKNOWLEDGMENTS

The author wishes to acknowledge Prof. Saleem Hashmi of the Department for Mechanical Engineering at Dublin City University, for allowing me to study this proposed course. To Dr. Tamas Szesi, for his guidance as my study leader, his humour, insight and help when I was writing this thesis. To Dr. Yann Delaure, for his suggestions, setting the standard and recommendations.

To my parents Jan and Heidrun Brink for their support in difficult times, in not giving up, which set an example to me. To my wife Retha, who kept me encouraged and ensure I stayed behind the books. I'll always love you.

To my company JV Tierney & Co. and in particular director, Mr. Tony Hogan, who turned a blind eye when I consumed so much time on my studies during work hours. For the people at DCU, who supported me in numerous ways. My thanks as well to Mr. Ed McIntyre from Mercury Engineering PLC, for his help in getting materials to construct the TE Collar. To Norma Stewart and Norman Flanagan for correcting my English and proof reading the final product.

Aan die Koning van die eeue, die onverderflike, onsienlike, alleenwyse God, kom toe die eer en heerlikheid tot in alle ewigheid.

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F. ABBREVIATIONS, UNITS AND SYMBOLS

Symbol	*Term Description*	*Abb. of Unit*	*Unit*
S_{AB} or α	Seebeck coefficient	μV/K	
n	Thermocouple Junction Pairs	-	
P	Power	W	Watt
		kW	kilowatt
		MW	Megawatt
P_e	Radiation Energy Absorbed	W	Watt
P_o	Electric Power output	W	Watt
P'_o	Electric Power output MTEG	W	Watt
P_r	Power ratio	-	Dimensionless
λ	TE Material Thermal Conductivity	W/m.K	
C	Heat capacity of Thermopile	J/K	
m	Mass	kg	kilogram
C_p	Specific Heat	J/kg.K	
Q	Heat Flow	J/kg	Joule/ kilogram
Q	Heat	J	Joule
L	Length	m	meter
		cm	centimeter
		mm	millimeter
l	Leg element length	m	meter
l_p, l_n	Length of p and n leg elements	m	meter
A	Cross Sectional Area	m^2	Square meter
A_p, A_n	Cross section area of p and n legs	m^2	Square meter
k	Conductivity of Material	W/m.K	Watt/meter Kelvin
τ	Thermal Time Constant	-	Dimensionless
V	Output voltage	V	Volt
		mV	millivolt
		kV	kilovolt
R	Resistance	Ω	Ohm
		mΩ	milliohm
		MΩ	Mega ohm
r	Internal Resistance	Ω	Ohm
t	Time	s	seconds
ρ	Density	kg/m^3	Kilogram/ cubic meter
f	Frequency	Hz	Hertz
α or *S*	Thermo Power	V/K	Volt/ Kelvin
η	Efficiency	%	Percentage
emf	Electro Motive Force	V	Volt
σ_B	Boltzmann's constant	-	Dimensionless
π or P	Peltier Coefficient		
β	Thomson Coefficient		
ρ_e	Electrical Resistivity		
I	Current	A	Ampere
		mA	milliampere
		μA	microampere
Ĭ	Current in multistage generator	A	Ampere
I_r	Current ratio	-	Dimensionless
λ_p, λ_n	Thermal Conductivity of p and n legs	W/m.K	Watt/ meter Kelvin

Symbol	*Term Description*	*Abb. of Unit*	*Unit*
E	Energy	J	Joule
		Wh	Watt-hour
		kWh	Kilowatt-hour
T	Temperature	K	Kelvin
H	Enthalpy	kJ/kg	Kilojoule/ kilogram
h	Latent Heat	kJ/kg	Kilojoule/ kilogram
S	Entropy	kJ/K	Kilojoule/ Kelvin
G	Irradiation- radiant energy	W	Watt
J	Radiosity- radiant energy	W	Watt
h	Specific enthalpy,	kJ/kg	Kilojoule/ kilogram
C	Heat transfer coefficient	-	Dimensionless
U	Internal Energy	J	Joule
Z	Figure of Merrit	-	Dimensionless
E	Conductance	S	Siemens
E	Electrical or Thermal Conductance	$W/m^2.K$	Watt/ Sq.meter Kelvin
m'	Mass Flow Rate	kg/s	Kilogram/ second
F	Force	N	Newton
P	Pressure	Pa	Pascal
		kPa	Kilopascal
N_A	Avogadro's Number	-	Dimensionless
ε	Emissivity	-	Dimensionless

ADP	Adenosine Diphosphate
ASC	Absolute Seebeck Coefficients
ASE	Absolute Seebeck Effect
ASHRAE	American Standard for Heating, Refrigeration and Air-conditioning Engineering
ATP	Adenosine Tri-phosphate
BMR	Basal Metabolic Rate
CIBSE	Chartered Institute of Building Service Engineers
CHP	Combined Heat and Power
COP	Coefficient of Performance
emf	Electromotive Force
EMI	Electromagnetic Interference
ESIOP	Economic and Social Infrastructure Operational Programme
EC	European Commission
EU	European Union
FAD	Flavin Adenine Dinucleotide
GDP	Gross Domestic Product
GIS	Graphite Impact Shell
HSR	Heat Sink Resistance
IEA	International Energy Agency
MPTG	Miniature Personal Thermoelectric Generator
NAD	Nicotinamide Adenine Dinucleotide
NCCS	National Climate Change Strategy
NDP	National Development Plant
Ni-Cd	Nickel Cadmium
Ni-MH	Nickel-Metal Hydride

RE	Renewable Energy
RF	Radio Frequency
RSC	Relative Seebeck Coefficients
RSE	Relative Seebeck emf
RTG	Radioisotope Thermoelectric Generator
SEI	Sustainable Energy Ireland
SCADA	Supervisory Control and Data Acquisition
TCA	Tri-Carboxylic Acid
TE	Thermoelectric
TED	Thermoelectric Device
TEM or TM	Thermoelectric Modules
TEG	Thermoelectric Generators
TPER	Total Primary Energy Requirement
VHF	Very High Frequency

Chapter 1- Miniature Personal Thermoelectric Generator (MPTG)

1.1 Summary

Heat, light and motion are the purest form of energy available. Increased environmental awareness, the introduction of international regulations concerning the usage of natural energy resources, waste management and the decrease of fossil fuels, require for economical development and the addressing, harnessing and utilisation of energy. This research project addresses the potential of converting electricity from waste heat or human body heat through thermocouple application in the light of new thermopile semiconductor development.

1.2 Introduction

Although Thermoelectric Generators (TEG) has many applications from micro-wattage to multi-kilowatt generation, the field of this research paper is restricted to Miniature Personnel Thermoelectric Generation (MPTG). Technology expanded exponentially in the amount of inventions in the beginning of the 19^{th} century. Again, after the two world wars, the technology advances were tremendous. Yesterday's science fiction is today's fact.

The building block of MPTGs is the thermocouple. Thermocouples are used primarily in the industrial world as temperature measurement device, utilising the concept of dissimilar metals A and B, joined together at one end, which produce a small unique voltage at a given temperature. Thomas Seebeck and Jean Peltier first discovered this phenomenon that forms the basis of thermoelectrics. Seebeck found that if you placed a temperature gradient across the junctions of two dissimilar conductors, electrical current would flow. Peltier, on the other hand, learned that passing current through two dissimilar electrical conductors, caused heat to be either emitted or absorbed at the junction of the materials. In practice, these thermocouples are connected in series in order to increase the generated voltage and for sensitivity of measurement. The findings of Seebeck and Peltier resulted in the development of a system called a thermopile. The name derives from the original sketched instrument of Nobili (1835).

Modern semiconductor technology has advanced to such a stage that thermopiles consist of hundreds of thermocouples in an area of a few square millimetres. Although these thermopiles are extremely small, production is inexpensive and mass production is possible. This makes the usage of these devices very robust and easy to operate as well as attractive to the industry. Modern production now produces thermoelectric 'modules' (TE) that deliver efficient solid state heat-pumping for both cooling and heating; many of these units can be used to generate DC power in special circumstances like the conversion of waste heat from the human body.

Heat can be transmitted in three modes: conduction, convection and radiation. Radiation as a heat transfer mode is particularly important to enclosed environments find in flues and cumulative pre-heating effects in accelerated and high burning. For this research paper, the heat transfer modes shall be considered for the proposed application. Thermopiles can operate over a broad temperature range without temperature stabilisation. Thermopiles are basically passive devices, generating a voltage proportional to the incident infra-red emissions.

The aim of this research is to investigate the utilization of Thermoelectric Modules (TM) for the generation of electricity from body heat.

The research question: Will the usage of these devices create enough energy to be utilised for miniature personal electro-generation in this application?

Due to the low heat emissions of body heat (around 34°C measured surface temperature) and the low temperature difference between the ambient and body temperatures (ΔT), the electricity generated from TM is extremely low, in the region of 50mV. This would require additional TMs connected in series to increase the voltage or additional p-n or metal-to-metal connections. Incorporating heat and cold sinks improve the heat flow performance. Since body heat generation is stable and under a fairly constant temperature, the 'ΔT' may be increased via heat sinks with fins to allow airflow and additional cooling when walking or running. This would mean the positioning of such modules must be of such nature that it is exposed and have unrestricted airflow around the cold sinks.

A reflective shield must be created between the heat and cold sinks to ensure no carry-over of heat flow from the heat to the cold sink. Insulation between the hot and cold junctions plays a vital part. This would increase the performance of the TM considerably. The heat sink surface connection and contact to the body area and position is vital to ensure optimum heat transfer from the body across the heat sink surface to the TM.

1.3 Significant prior research

The first work on thermocouples originates from Thomas Johann Seebeck (1822), who found that small electric currents flow in closed circuit that consist of two unlike conductors when a temperature difference exists between their junctions [2]. Further contribution to thermoelectrics was done in 1834, when Jean Charles Athanase Peltier observed temperature changes between two dissimilar materials when a current passes. In 1838 Lenz concluded that heat is absorbed or generated at junctions between two conductors depending on current direction. In 1850 Lord (Thomas) Kelvin established the relationship between Seebech and Peltier, called the Thomson effect. In 1885, Rayleigh first considered the possibility of thermoelectric generation of electricity. Within 60 years, the concepts of thermoelectrics were established.

Current research focuses on remote sensing utilising thermopile sensors and via thermopile employment for gas detection by infra-red absorption in industrial usage. Silicon micromachined thermopiles commercially entered the infra-red detector scene in the beginning of the 1990's. Recent development in thermophotovoltaic utilization of infra-red sensitive photovoltaic cells generate electricity directly from waste heat which is about 100 times more effective in energy conversion than traditional solar cells.

Utilizing the 'inverse Peltier' effect, thermoelectric heat pumps are now commercially available. This 'inverse Peltier' or Seebeck effect is responsible for the generation of thermocouple voltage signal. Today, these devices operate on the Peltier effect of a voltage supplied to the thermoelectric heat pump, pumping heat from one array across the two connections of dissimilar materials to the other side, cooling integrated circuits in computers. Figure 1-1 depicts the structure of the type thermocouple used (Tellurex, 2002).

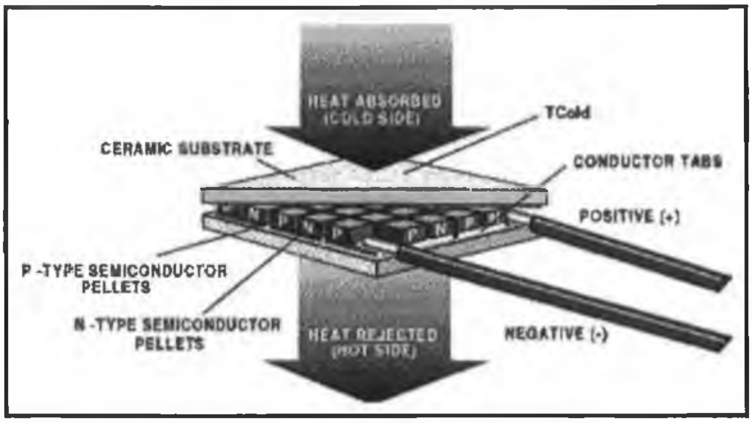


Figure 1-1 Thermocouple Plate (Tellurex, 2002)

Another new field is the usage of RTGs (radioisotope thermoelectric generators) used by interplanetary satellites to generate their onboard system power in outer space. An RTG uses radioactive material (like ^{238}Pu) to generate heat, and thermocouples convert this heat to electricity. RTGs have no moving parts, so they are reliable, and the radioactive material generates the heat ensuring a reliable energy source for 8 to 12 years. This makes these devices more attractive than solar panels since solar panels are only effective near a solar emitting source. RTG devices were made famous on the Voyager missions into outer space.

Research suggest that 'A good thermoelectric material must have a large Seebeck coefficient to produce the required voltage, high electrical conductivity to minimise the thermal noise, and a low thermal conductivity to decrease thermal losses from thermocouple junctions [1]. Research on thermoelectric energy conversion generally focused on finding or developing such materials. New results indicates that the performance of a good thermoelectric semiconductor can be greatly enhanced by the addition of emitter layers and compensation layers, so that the resulting conversion efficiency is no longer limited in the same way by the material parameters.

<u>The research question:</u> Is it therefore feasible to study the applications for waste heat electrogeneration utilising thermopile application methods?

1.4 Research objective

The objective of this research is to develop a generator of electricity that works as a collector and transformator of body heat energy into usable electricity. The use of modern materials combined with advances in technology in semiconductors and silicon micro machining of thermopiles create an alternative cost effective way to produce electricity out of waste heat and other heat sources. The research focuses on utilising and conveying body heat emissions to electricity. Introduction of heat sinks into the generation system increases the heat flow and boosted system efficiency. This research focuses on the (human body) thermal heat emissions, approximate at 37°C internal temperature, to convert the temperature difference into electrical power to drive compact equipment, like CD players or radio's and to view the practability of doing so. The work will consist of calculation, design, building a prototype generator model, testing and evaluation of this model or generator.

1.5 Research methodology

Thermopiles sense IR light or heat through a number of tiny thermo elements placed below an absorber area. The IR light or heat that strikes the absorber heats up and generates a voltage at the output leads. The output is a DC voltage, which is a direct measure of the incident radiation power, P_{rad}. The voltage output signal, V_{out}, is typically in the several 10μV range and needs amplification. The height of the voltage is determined by the so-called sensitivity of the thermopile, *S*, which is defined as thermopower and measured in V/W.

$$S = V_{out}/P_{rad} \quad (1.1)$$

$$Z = \alpha 2/\rho\lambda \quad (1.2)$$

A material's thermoelectric figure of merit is defined by '*Z*', where 'α' is the Seebeck coefficient, 'ρ' the electrical resistivity, and 'λ' the thermal conductivity. Thermocouples rely on this Seebeck effect. Although almost any two types of metal can be used to make a thermocouple, a number of standard types are used because they possess predictable output voltages and large temperature gradients. The K type thermocouple, which is the most popular, at 300°C will produce 12.2mV

The total thermopower, 'α' measured in V/K generated, is the temperature difference 'ΔT' between the hot and cold ends of the individual thermocouples.

$$\alpha = V_{out}/\Delta T \quad (1.3)$$

During the research, the heat emissions and the thermopile electrogeneration will be measured as well as cooling methods for the cold side of the thermopile to ensure optimum voltage generation. The two dissimilar materials, which form the thermocouple, generate a DC current from the heat. The DC current will be subjected through a series of these thermopiles to allow higher voltage be generated. The aim is to generate enough energy to drive personal electrical compact equipment from the body 'waste' heat.

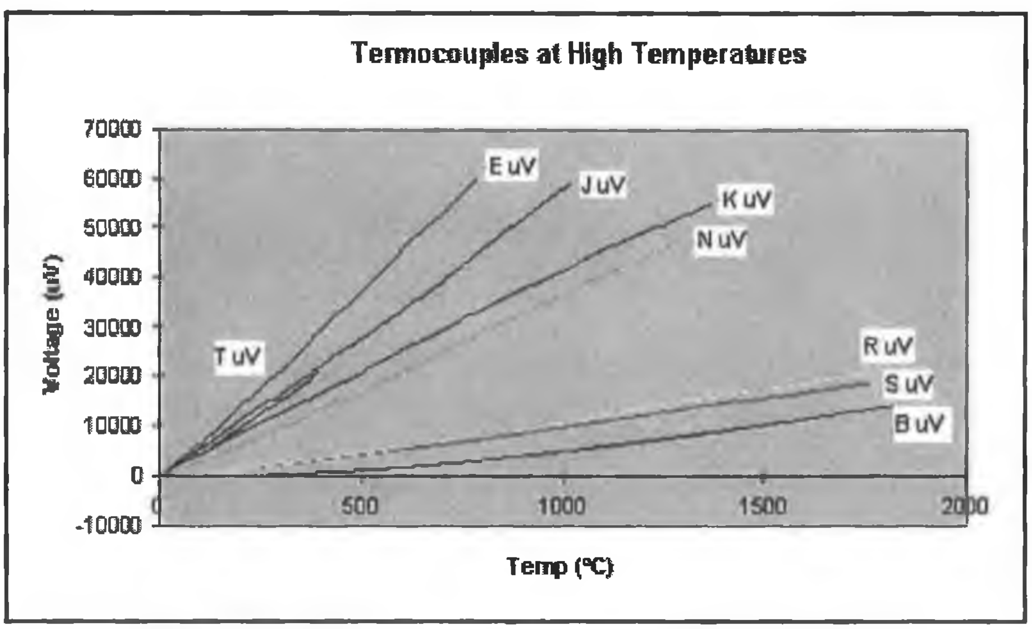


Figure 1-2 Thermocouple at High Temperature (Omega USA)

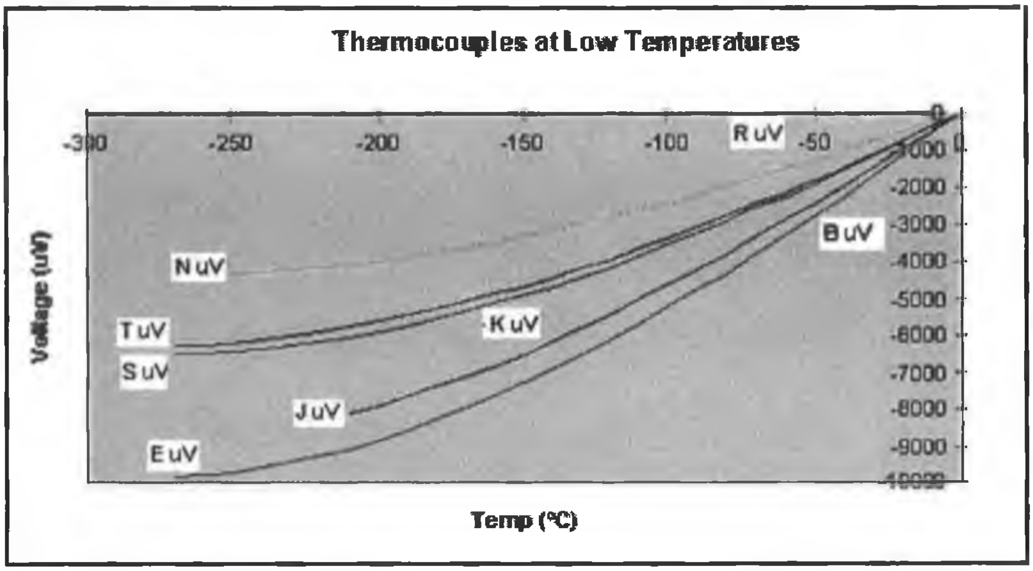


Figure 1-3 Thermocouple at Low Temperature (Omega USA)

The following table provides a summary of basic thermocouple properties:
Common commercially available thermocouples are specified by ISA (Instrument Society of America) types. Type E, J, K, and T are base-metal thermocouples and can be used up to about 1000°C (1832°F). Type S, R, and B are noble-metal thermocouples and can be used up to about 2000°C (3632°F).

ISA	Material (+ & -)	Temperature Range °C (°F)	Sensitivity@ 25°C (77°F) µV/°C (µV/°F)	Error*	App.**
E	Chromel & Constantan (Ni-Cr & Cu-Ni)	-270~1000 (-450~1800)	60.9 (38.3)	LT:±1.67°C(±3°F) HT:±0.5%	I,O
J	Iron & Constantan (Fe & Cu-Ni)	-210~1200 (-350~2200)	51.7 (28.7)	LT:±2.2~1.1°C(±4~2°F) HT:±0.375~0.75%	I,O,R,V
K	Chromel & Alumel (Ni-Cr & Ni-Al)	-270~1350 (-450~2500)	40.6 (22.6)	LT:±2.2~1.1°C(±4~2°F) HT:±0.375~0.75%	I,O
T	Copper & Constantan (Cu & Cu-Ni)	-270~400 (-450~750)	40.6 (22.6)	LT:±1~2% HT:±1.5% or ±0.42°C(±0.75°F)	I,O,R,V
R	Platinum & 87% Platinum/ 13% Rhodium (Pt & Pt-Rh)	-50~1750 (-60~3200)	6 (3.3)	LT:±2.8°C(±5°F) HT:±0.5%	I,O
S	Platinum & 90% Platinum/ 10% Rhodium (Pt & Pt-Rh)	-50~1750 (-60~3200)	6 (3.3)	LT:±2.8°C(±5°F) HT:±0.5%	I,O
B	70% Platinum/ 30% Rhodium & 94% Platinum/ 6% Rhodium (Pt-Rh & Pt-Rh)	-50~1750 (-60~3200)	6 (3.3)	LT:±2.8°C(±5°F) HT:±0.5%	I,O
*:	LT = Low temperature range, HT = High temperature range				
**:	I = Inert media, O = Oxidizing media, R = Reducing media, V = Vacuum				
	Constantan, Alumel, and Chromel are trade names of their respective owners.				

Table 1-1 Thermocouple Properties (eFunda)

1.6 Importance of the research

The world is dependent on converting energy to electricity and it is of a strategic nature that countries consider natural resources and energy converting technology. When fossil fuels cease, will there be an alternative energy generation in position to replace fossil fuel power stations and transport?

The natural resources in the world are expiring at a significant rate. Calculations on the usage of fuels such as oil, coal and gas indicate that resources will be exhausted by the projected year 2040. Alternative ways of creating clean energy is critical, as these resources cannot be replenished to meet the rate of demand.

The greenhouse effect on the global environment is of further concern due to global warming. The effect called greenhouse, produces gases that allow incoming solar radiation to pass through the Earth's atmosphere, but prevent most of the outgoing infrared radiation from the surface and lower atmosphere from escaping into outer space. This process occurs naturally and keeps the Earth's temperature at about 300˚K. Current life on Earth could not be sustained without this natural greenhouse effect. Widespread use of clean energy sources and renewable energy like thermoelectrics could contribute to breaking the dependency on the use of fossil fuels. This in turn would considerably reduce the amount of carbon dioxide produced, as well as reducing the levels of the pollutants which cause global warming and acid rain.

A further consideration is the pollution caused by normal solid batteries used in appliances. No technology exists to recycle these spent cells satisfactorily.

Since the primary research focuses on the generation of electricity for electrical compact equipment, the amount and dependence of batteries used by these devices would reduce, creating less waste.

1.7 Limitations and key assumptions

Thermopiles generate a small amount of voltage at μV. Combining these small amounts of voltages in series, the total voltage amount will then be boosted from a DC-DC converter according to the voltage requirement for commercial and industrial applications.

The thermocouple can only recover from processed heat >2% if we abide to the Carnot cycle. The thermocouples need to maintain a low temperature on the cooling side either with water convection, forced air or heat sinks;

$$\eta_{carnot} = 1 - T_b / T_{amb} \quad \text{or,} \qquad (1.4)$$

$$\eta_{carnot} = (T_b - T_{amb}) / T_b \qquad (1.5)$$

The temperature ranges play a role, as this would influence directly the voltage output of each thermopile in the system. This also effects voltage fluctuations with inconsistent temperatures.

Sensitivity is low, usually 50µV/°C (28µV/°F) or less. Its low voltage output may be masked by noise. This problem can be improved, but not eliminated, by better signal filtering, shielding, analog-to-digital (A/V) conversion or utilising DC-DC converters.

Many researchers have worked to convert heat to electricity directly without the moving parts of a generator. Among other advantages, such a device would be virtually silent, vibration-free, and low in maintenance costs. Until now, however, the efficiency of such thermoelectric devices has been a problem. The amount of electricity they produce from a given amount of energy has been low.

1.8 Contributions and key assumptions

The expectation of this research is that it will contribute to the understanding of thermocouple and piles in the electrogeneration field and that this unique method of practical application of utilising waste heat to help with practical solutions in today's energy quest.

The key assumptions to fulfill the research requirements is that thermopiles would be of a higher efficiency due to new innovative construction methods in the semi-conductor industry.

Chapter 2- Sources of Electric Voltage

2.1 Introduction

Electricity today is a means of utilising other energies or fuels to handle, harness, convert or generate, and managing such energy to one format. In fact, most of today's application of energy is in and for the form of electricity. It is therefore vital to consider other means and types of electricity conversion processes, generation methods and applications.

2.2 Summary of Sources of Electric Voltage in Scientific and Engineering Utility

Electro-mechanical generators generate voltage by mechanically changing the flux linkage of coils, as in rotating generators. They vary from miniature devices to rotating utility generators producing megawatts. They range from intermittent, generating a single pulse at each mechanical motion, short term as in plunger type explosive detonators, to steady state power plants with continuous rotation. The frequency may be anywhere from DC to low radio frequency (RF). Household 50 Hz power comes from such generators.

Primary batteries. Any two metals, or a metal and graphite, generate a voltage between them when they are joined by an electrolyte, typically a water solution of an ionised acid. Typical voltage is 1.5 volt per cell and it is common practice to connect several cells in series. Dry cells are such wet cells with a minimum amount of water sealed in. One of the metals goes into solution as the battery is discharged. (A *battery* is a combination of *cells* connected together in some combination of series and parallel. However a single cell is often referred to as a "battery.")

Secondary or storage batteries. These resemble primary batteries except that the electrodes are of the same material to begin with. When current is forced through by an external, or "charging" voltage, different electrolytic reactions occur at each electrode and energy is stored chemically. The battery becomes a source of voltage and current until it is discharged and returns to its original state. Automobile batteries are storage batteries, typically producing 12 volt.

Fuel cells. These are primary batteries in which a chemical reaction is fueled by the continuous consumption of either electrode or electrolyte. They are not yet commercially available but in the future are expected to be made in high power sizes. Experimental fuel cells already power some automobiles and satellites.

Solar cells. These are solid state cells which convert a portion of incident light energy to electricity. These cells can be connected in series and parallel to form a DC power supply battery. Most satellites are powered by solar cell arrays. The future expectation is that solar cell arrays could be made cheap enough to be a source of utility power for everyday application.

Piezo-electrics. Quartz and certain ceramics generate voltage when mechanically strained. Very little current can be drawn, since they are insulators, but they are very useful transducers of mechanical stress and strain

Electrets. These are storage batteries in which a charge is frozen into an insulator. It produces an electrostatic voltage but can provide no current.

Lightning. Lightning is the discharging of enormous voltages of energy stored in clouds. As yet no means of using this energy has been developed, but enormous efforts are made to prevent damage to buildings and utility systems.

Thermo-electrics. Two pair of junctions between two dissimilar conductors, if held at different temperatures and connected in series, produced a voltage. A thermopile is comprised of stacks of such junctions. Some thermopiles have been heated in satellites by nuclear decay heat. Thermocouple temperature transducers are thermo-electrics.

Biological voltage generators. Electric eels generate enough voltage to give a serious shock. The human brain generates voltages and operates by the flow of current pulses between brain cells. (The junctions are electro-chemical.) It also sends voltage signals to the heart and other muscles. Sensor cells generate voltages that send currents to the brain. These voltages on the skin can be measured by electro-cardiographs, electro-encephalographs and pulse rate monitors.

Friction between two insulators produces electrostatic voltages on the insulators.

Capacitors store electric charge provided by an external source of voltage and then discharge it when connected to a load. The energy and voltage stored by different capacitors range from extremely small to enormous. Capacitors are use to accumulate energy slowly and then discharge it in an enormous high voltage and high current pulse [1].

2.3 Summary of Sources of human-powered schemes

The human body is an energy source. The most effective way to tap this energy source has yet to be determined. The following research is currently being done to discover human-powered devices for the generation of electricity or energy:

Piezoelectric devices: Piezoelectric substances, like some ceramics, also generate electrical energy from mechanical strain but without the need for voltage to be applied. This well-understood material is the core of "heel strike" devices that generate electricity from walking. "Generating 1-2 watt per shoe is not out of the question. A major issue that remains is the durability of these devices," Dr. Robert J. Nowak, program manager for energy harvesting at Darpa, wrote to *SPACE.com.* Great for soldiers, bad for astronauts: "giant steps are what you take, walking on the moon."

Urine-based fuel cell: Urea has to be subjected to enzymatic hydrolysis to make carbon dioxide and ammonia, and then oxidize the ammonia to nitrogen and water. But the Center for Space Power and Advance Electronics notes that "one problem with the system is the need for alkaline conditions that may require transport of sodium hydroxide, a hazardous compound. Also, to achieve power generation in the range of 0.5 - 1W, a system to concentrate the breakdown products of urea, such as reverse osmosis, will be necessary. However, for astronauts and soldiers on the run, one attractive feature of this fuel cell concept is the production of water as a by-product of the system."[2]

Inertial energy scavenging: Some Seiko watches are powered by a weight that swings as the wearer moves, driving a tiny generator. It is not expected that much energy can be generated from these systems, however, deployed to each element needing electricity could generated a useful amount of inertia energy to equipment.

Electromagnetic generator: Large muscular groups (especially in the legs) can generate electricity by simple motions against gravity and small direct current permanent magnet motors. However, the Center for Space Power and Advance Electronics cautions, "there is little or no efforts within the scientific community to design efficient small generators of the type needed for harvesting of human energy."[2]

Thermoelectric materials: These materials convert body heat into electricity by using combinations of materials (metals or semiconductors) that are poor thermal conductors and good electrical conductors. When two of these materials with different temperatures come into contact, electrons migrate, charging a battery or creating usable current through something called the Seebeck Effect. The disadvantage is the requirement for great temperature differences to obtain significant energy while "on Earth most places are pretty close to body temperature," notes Dr. Henry Brandhurst[2].

The latest application of a thermocouple on the market is the Verichip, manufactured by Motorola. This chip is in the process of replacing the conventional credit card as a means of financial identification. The thermocouple uses the body temperature fluctuations to charge a Lithium battery under the skin. Although it is still under research, global acceptance of this device has already been established.

Chapter 3- Heat Conduction MPTG

"Covert military operations and space shuttle missions are both burdened by the fact that they rely on an inefficient, energy-wasting machine: the human body. Considering one of the biggest logistical problems planners face is getting power to equipment in remote places like Afghanistan or the moon, researchers are devoting their efforts to cut some of those losses through 'energy harvesting' from the human body." [6]

3.1 Introduction

In order for the Miniature Personal Thermoelectric Generator (MPTG) to conduct heat, a large number of thermocouples need to be connected electrically in series to create a thermal path between the body heat sample and the surrounding heat sink. The combination of these thermocouples constitutes a thermocouple plate or a thermopile serving as a Thermoelectric Generator (TEG). Thermopiles are commercially available as cooling units used in refrigeration or electronic equipment such as computers. They operate based on the Peltier cooling effect, a phenomenon discovered in the early 19^{th} century. When a voltage is applied at the junction of two dissimilar conductors A and B, that junction will either absorb or release heat, depending on the polarity of the voltage applied. The reverse of this process also takes place and generates a voltage in relation to the temperature at the junction.

According to the inverse Peltier effect, if the junction of two dissimilar conductors A and B is cooled down or heated, a voltage will be generated at that junction. The most common material used to make Peltier TM (Thermoelectric Modules) are n- and p-doped bismuth telluride (Bi-Te) semiconductors. Chapter 3 gives an in-depth study to these Modules.

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

3.2 Construction and Materials used for the MPTG

The building block of the MPTG is the thermocouple made of an n-type semiconductor cube in contact with electrically conductive material at each end. The second dissimilar conductor in this arrangement are actually the copper connections. Therefore, there are two junctions at the ends of the semiconductor cube, one cold and one hot junction. See Figure 3.1. The repetition of this arrangement gives a thermocouple plate that can be used to pump heat away from a hot surface or heat source. To make these devices more efficient, the thermocouples are connected in thermally in parallel and electrically in series. The parallel thermal combination ensures a higher thermal conductivity of the unit and therefore higher efficiency of the thermoelectric device. Chapter 4 gives in in-depth study in on this installation.

The thermocouple operation is based on the Seebeck effect; thus, the amount of electrical potential produced can be interpolated as a measure of temperature difference. Thermocouples have nearly linear temperature to electromotive force (emf) characteristics.

$$\Delta V = S_{AB}\,\Delta T \qquad (3.1)$$

where 'S_{AB}' is the relative Seebeck coefficient, expressed in mV/K. This coefficient depends on the temperature and the two materials used in the thermocouple. A sign is assigned to the Seebeck coefficient according to the sign of the potential difference related to the temperature difference. However, it is much more convenient to work with absolute values: the magnitude of the Seebeck coefficient of a junction is then calculated as the absolute value of the difference between the Seebeck coefficient of each metal; that is,

$$S_{AB} = | S_A - S_B | \qquad (3.2)$$

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

$$\Delta V = n\,S\,\Delta T \qquad (3.3)$$

Such a device is called a thermopile. The elements of a series of thermocouples of alternate material A and B are placed between a heat source and a heat sink. The hot junction comes into thermal equilibrium with the high temperature surroundings producing an emf at the leads. If a current flow results, thermal energy is converted into electrical energy. The remaining energy absorbed at the hot junction is rejected to the heat sink at the cold junction.

The TEM consists of an array of Bismuth Telluride semiconductor pellets that have been 'doped' so that one type of charge carrier– either positive or negative– carries the majority of current. See Chapter 4 for more detail on Transport of Heat and Electricity in Crystalline Solids. The TE modules used in the MPTG are commercially available from thermoelectric manufactures. These devices can be used either in the Peltier mode for refrigeration or in the Seebeck mode for electrical power generation. The device structure comprises of p and n thermoelements sandwiched by two high thermally conducting but electrically insulating ceramics. See Table 3.1 for material properties.

Material	**Density g/cm^3**	**Specific Heat Capacity mJ/g/K**	**Thermal Conductivity mW/cm/K**
TE Material	7.175	178.5	16.7
Ceramics	3.7	775	346
Copper Tab	8.91	385.2	4000
Solder	8.56	167	326.5
Water	1000	4.18	5.89

Table 3.1 Material Property Table

The pairs of P/N pellets are configured so that they are connected electrically in series, but thermally in parallel. Metalized ceramic or Aluminium substrates provide the platform for the pellets and the small conductive tabs that connect them. The pellets, tabs and substrates form a layered configuration in a practical square form. Module size varies from less than 5x5mm to approximately 40x40mm. TEMs can function singularly or in series, parallel, or series/parallel electrically connected. Series function increase the voltage generated, parallel connection increases the current and series-parallel increases the overall voltage and current to the circuit.

The system is assembled via mechanical clamping of the TE modules with silicon bonding to the heat sinks. TEMs are comparatively strong in compression and weak in shear, therefore, excessive mechanical loading of the module in the installation is avoided. Thermal resistance occurs at each interface of an assembly with another and affects overall system performance and efficiency.

Due to the bending radius of the TE Collar the mechanical clamped model is filled with interface materials to fill in the small thermal gaps. Silicone-based metal oxide thermal oil or highly thermally conductive compounds are used. Uniform pressure is applied with mechanical clamping to ensure thermal contact with the heat sinks and TEMs during the installation. Although it is almost impossible to manufacture an identical positioning, clamping and thermal contact with every TEM, the efficiencies are greatly affected by this installation procedure.

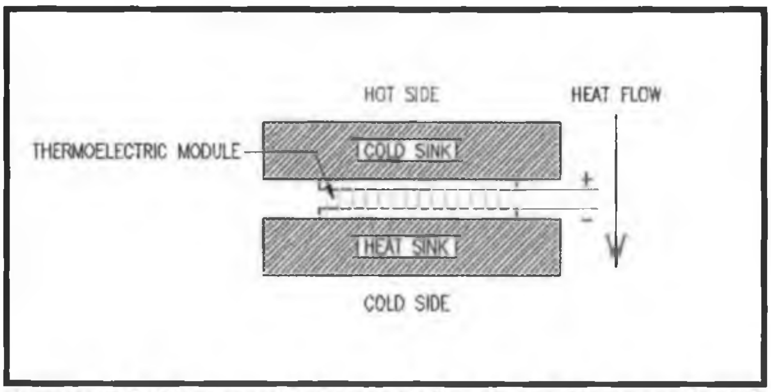


Figure 3.1 Thermopile layout of a single Thermoelectric Module

2.3 Heat flow in Thermoelectric Generator

In power generation Thermoelectric Modules (TEMs) are positioned between the heat emitter and the heat sink. The heat generated passes through the thermopile and dissipates into the heat sink as indicated in Figure 3.1. The thermopile voltage (V) proportional to the heat flux (P) can be measured across the leads of the thermopile. The heat is transferred from the body to the heat sink quantitatively, (see Chapter 5 on the heat generated by skin temperature) and effectively discharged into the outside environment.

Employing the Seebeck effect, thermoelectric power generators convert heat energy to electricity. When a temperature gradient is created across the thermoelectric device, a DC voltage develops across the terminals. When a load is properly connected, electrical current flows. With this application, power supply is provided via the MPTG to compact equipment.

MPTGs are influenced by many factors. The most important variables are ambient temperature, physical and electrical characteristics of the TEM employed, and efficiency of the heat dissipation system or heat sinks. The MPTG device has the physical characteristics to incorporate the TEMs in direct contact with hot and cold heat sinks.

The charge carriers in the semiconductor material will therefore relocate the heat from the neck of the body to the heat sink. This causes the temperature of the heat sink to rise. When the temperature of the heat sink exceeds that of the surrounding air, heat will flow naturally from the sink to the atmosphere.

	Positive Test Mode		**Negative Test mode**	
	Heat Entering Cold Junction	**Heat Exiting Hot Junction**	**Heat Entering Cold Junction**	**Heat Exiting Hot Junction**
1. Module Peltier	$-N \times \alpha \times I \times T_c$	$-N \times \alpha \times I \times T_h$	$-N \times \alpha \times I' \times T_c'$	$-N \times \alpha \times I' \times T_h'$
2. Module Conduction	$N \times k \times (T_h - T_c)/L$	$N \times k \times (T_h - T_c)/L$	$N \times k \times (T_h' - T_c')/L$	$N \times k \times (T_h' - T_c')/L$
3. Internal Radiation	$Ri\ (T_h^4 - T_c^4)$	$Ri\ (T_h^4 - T_c^4)$	$Ri\ (Th'^4 - Tc'^4)$	$Ri\ (Th'^4 - Tc'^4)$
4. External Radiation	$Re\ (T_a^4 - T_c^4)$	$Re\ (T_h^4 - T_a^4)$	$Re\ (T_a'^4 - T_c'^4)$	$Re\ (T_h'^4 - T_a'^4)$
5. Convection	$H \times (T_a - T_c)$	$H \times (T_h - T_a)$	$H \times (T_a' - T_c')$	$H \times (T_h' - T_a')$
6. Air conduction	$K_a \times (T_a - T_c)$	$K_a \times (T_h - T_a)$	$K_a \times (T_a' - T_c')$	$K_a \times (T_h' - T_a')$
7. Wire Conduction	0	$W \times (T_h - T_w)$	$W \times (T_w - T_c')$	0
8. Module joule	$I^2 \times R/2$	$-I^2 \times R/2$	$I'^2 \times R/2$	$-I'^2 \times R/2$
9. Wire Joule	0	$-I^2 \times R_w$	$I'^2 \times R_w$	0

Table 3.2 Junction Heat Load Calculations for a TE Module [7]

Sum of Junction Heat Load calculations for a TE Module	
1. Module Peltier	$Q_p = -N \times \alpha\ \{I\ (T_h - T_c) + I'\ (T_h' - T_c')\}$
2. Module Conduction	$Q_k = 2 \times N \times k\ (T_h - T_c - T_h' - T_c') / L$
3. Internal Radiation	$Q_{ri} = 2 \times K_{ri}\ (T_h - T_c - T_h' - T_c')$
4. External Radiation	$Q_{re} = K_{re}\ (T_h - T_c - T_h' - T_c')$
5. Convection	$Q_c = H\ (T_h - T_c - T_h' - T_c')$
6. Air conduction	$Q_a = 2 \times K_a\ (T_h - T_c - T_h' - T_c')$
7. Wire Conduction	$Q_w = 0$; since $T_w = T_h = T_c'$
8. Module joule	$Q_{wi} = 0$; since I w I'
9. Wire Joule	$Q_{wi} = 0$; since I w I'

Table 3.3 Sum of Junction Heat Load calculations for a TE Module [7]

Where:

N	total number of TE pellets
α	TE material Seebeck coefficient
I , I'	Electrical current in POS and NEG modes
T_h , T_h'	Hot junction temperature in POS and NEG modes
T_c , T_c'	Cold junction temperature in POS and NEG modes
k	TE material thermal conductivity
L	Length/ area of TE pellet
R_i	$\sigma \times \varepsilon \times$ Internal surface area
R_e	$\sigma \times \varepsilon \times$ External surface area
σ	Boltzman constant
ε	Effective emissivity (including shape factor)
H	Convection coefficient x External surface area
K_a	Air conductivity x Internal space area

W	Sum of wire thermal resistance
R	TE module electrical resistance
R_w	Electrical current wire resistance
T	$(T_h + T_c) / 2$
$T_h^4 - T_c^4$	$= 4 \times T^3 \times (T_h - T_c)$
K_{ri}	$= 4 \times T^3 \times R_i$
K_{re}	$= 4 \times T^3 \times R_e$

3.4 MPTG system description and make-up

The neck or upper arm may be used because this location is out of obstruction and between the higher limits of main arteries and skin blood flow which emit a higher heat output than other parts of the body (Refer to Figure 5.5). The neck is the best location since it is generally exposed, free from clothing and the natural flow of air decimates the heat in the heat sink, increasing effectiveness of the heat flow through the MPTG. The band consists of an adjustable strap, blackbody heat sinks, electrical wire and flexible cool sinks. See Figure 3.2 and 3.3

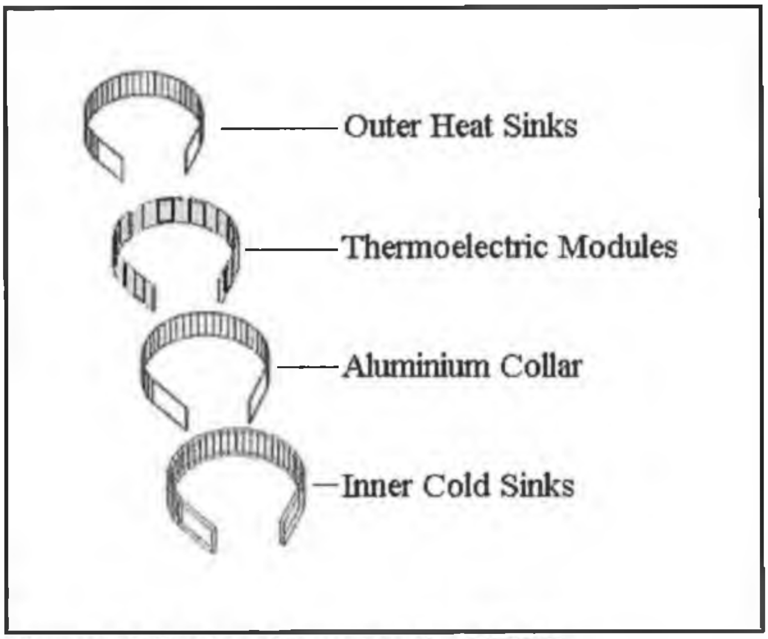


Figure 3.2 Sectional layout to the MPTG

The wire is connected to a voltage regulator, shunt regulator or DC-DC Converter to allow constant voltage and amperage generation without interference from temperature fluctuations. See Figure 3.5. Chapter 4 deals with the DC-DC Converter application in more detail.

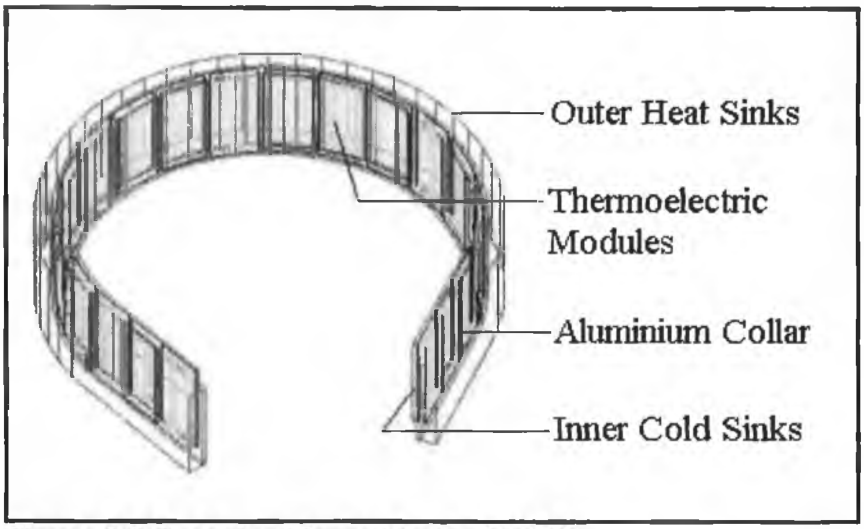


Figure 3.3 Combined layout to the MPTG

In Figure 3.4, the complete construction layout is indicated for the MPTG or Thermoelectric Collar. The TE Collar layout is based on an Alice-band form to allow flexibility and mechanical adjustable to ensure the heat sink firm fit to the skin of the neck.

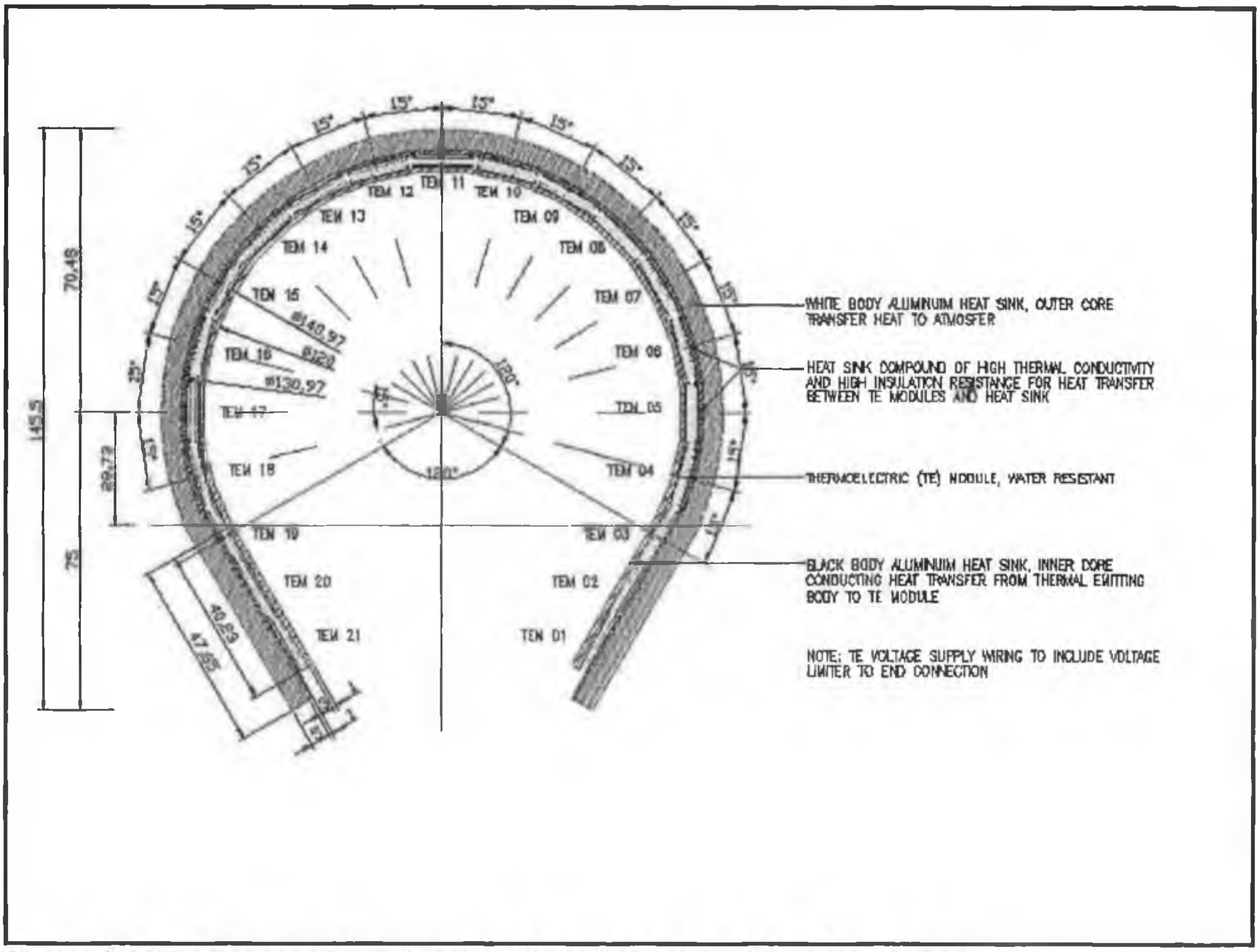


Figure 3.4 The proposed construction layout of the MPTG (TE Collar)

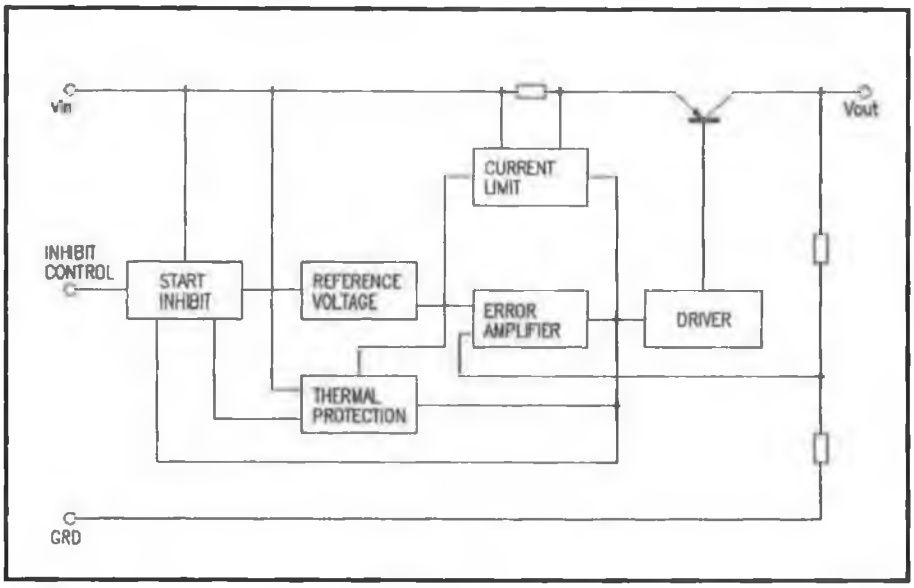


Figure 3.5 Schematic Diagram of Voltage Limiter

3.5 The configuration of the thermoelectric (TE) system

Conceptually this typical thermoelectric system is designed to generate electricity; The goal is to collect as much as possible heat from the body neck area, pump through the heat converter (Peltier device used as an electricity generator via the Seebeck effect) to the outside of the Collar, and release the collected heat into the ambient air. This is through employing two heat sink combinations in conjunction with multiple Peltier devices utilised for the heat to electricity conversion. Fundamentally, there are four basic components: a heat source, a TEG module (or thermoelectric generator), a 'cold-side' heat sink, and the electrical load. The system may also include a voltage regulation circuit, or a fan for the heat sink. The TE module is sandwiched between the heat source and the cold-side sink. Several TEG modules are used to connect in a series-parallel electrical combination to serve the external load.

Heat sinks shorter in length are used on the inside or 'hot side' of the TE Collar. This heat sink picks up the heat from the skin of the neck. The Peltier device is mounted or sandwiched between this 'hot side' sink and a larger sink on the 'cold side' of the system. (Refer to Figure 2.1) The natural flow of heat is always from hot to cold, so when heat from the body or skin temperature is applied to the thermoelectric module, heat flows naturally from the hot side (internal) to the cold side (external) of through the TE module.

As heat transfers through the thermoelectric device, it actively pumps heat from the hot side to the on the cold side via the Seebeck effect. On the cold side, the ambient air circulates between the sink's fins to absorb and dissipate some of this collected heat. The heat dissipated on the cold side not only includes what is pumped from the box, but also the heat produced within the Peltier device itself (V x I) or internal resistance. Some portion of the heat may be lost to the surroundings through the mechanical clamps or supports.

3.6 Heat and Cold Sinks used for MPTG

When utilising thermal electrogeneration, the thermal load requires heat sinks to accumulate heat (hot side) or dissipate accumulated heat into another medium (cold side air circulation). Without these provisions, the TE device will be vulnerable to overheating. When it reaches the flow property temperature of the solder employed, the TEM unit will be destroyed.

It would be virtually impossible to get an adequate ΔT without some type of heat sink. The size requirement for the heat sink fin surface area may be reduced with good natural airflow. The heat pumping capability of the TEM is significantly influenced by the efficiency of the heat sink. The hot side of the module must interface with an efficient heat removal system to achieve 'ΔT', useful across the module.

Heat sinks come in three types: Natural convection, forced convection, and liquid cooled. The thermal resistance varies among the different types and sizes of sinks with natural convection being the least efficient and liquid cooled the most efficient. For the application of the TE Collar, natural convection heat sinks are used. The rise in heat sink temperature above ambient temperature is almost linear with the heat dissipated by the heat sink. The heat sink performance is determined by this ratio, referred to as thermal resistance in °C/W or K/W [9]. Typical thermal resistance values of heat sinks range from:

1. From 2.0 to 0.5 K/W for natural convection;
2. From 0.5 to 0.02 K/W for forced convection; and
3. From 0.02 to 0.0005 K/W for liquid cooling [11]

For natural convection the heat sink thermal path to ambient must be carefully analysed to achieve the maximum heat transfer. Considerations must be given to the heat travel distance, type of materials used, mechanical interface losses and the surface exposed to the ambient temperature. Although the heat sink is the primary surface utilised to dissipate the heat, other surfaces in the thermal path exposed to the ambient temperature also contribute.

The temperature differential or gradient across the module can now be calculated as follows:

$$\Delta T = T_h - T_c \qquad (3.4)$$

The general thermoelectric equations for heat sink are as follows [10]:

$$T_h = T_a + (IV + Q_c)H \qquad (3.5)$$

where: $Q_c = S\,I\,T_c - I^2R / 2 - K\{T_c + (IV + Q_c)H - T_c\}$

$$V = S\{T_a + (IV + Q_c)H - T_c\} + IR \qquad (3.6)$$

To generalise these equations to independent geometry the following apply:

$$i = I\,L/A \qquad (3.7)$$

$$q_c = Q_c\,L/AN \qquad (3.8)$$

$$h = HNA / L \qquad (3.9)$$

$$v = V/N \quad (3.10)$$

This gives:

$$q_c = \alpha\, i\, T_c - i^2\, \rho/2 - \lambda\{T_c + (iv + q_c)h - T_c \quad (3.11)$$

$$v = \alpha\{T_c + (iv + q_c)h - T_c\}/\, \rho \quad (3.12)$$

where:

α	Material Seebeck Coefficient
ρ	Material Resistivity
λ	Material thermal Conductivity
S	Seebeck Coefficient ($S = N\alpha$)
R	Resistance ($R = N\rho L/A$)
K	Thermal Conductance ($K = N\kappa A/L$)
I	Current
V	Voltage
v	Device Voltage
T_a	Ambient Temperature
T_c	Cold side Temperature
H	Heat sink Resistance
N	Number of pellets in TEM
L	Pellet length
A	Pellet footprint area
Q_c	Heat pump capacity at cold junction
q_c	Heat flux at cold junction

In the MPTG, heat can be lost through heat paths other than the thermopiles. In the MPTG, whenever heat is applied to the surface of the hot side, it passes through the heat sink, through the ceramic of the thermopile, through two copper tabs or conductor electrodes, through the cold side ceramic to reaches finally the cold sink.

3.7 Design of MPTG to the Load

In MPTG system, one of the most important processes is reaching an understanding of the thermal load. The body thermal load and heat is discussed at great lengths in Chapter 5. This information is vital to design and choosing the best TE device for the thermal load and application. While the TE Collar system requires optimisation, the correct thermoelectric modules are therefore important to heat transfer which will compliment the system thermal loads Estimating the thermal load is therefore required before construction of the TE Collar in order to see the quantity heat removed from the thermal load to achieve the performance efficiencies.

The two thermal loads in any TE application are the passive and active loads. The active load is a thermal component and is found to be part of the load that produces heat. The passive load is defined as the component rate of energy moved. Due to the temperature gradient between the thermal load (the body) and the environment or ambient temperature, a certain amount of energy must be continually moved out from the load.

With a TE system, thermal load must be hotter (or colder in hot environments) than the ambient temperature. There will be some heat transfer 'leaking' away from the TE system. This may be reduced by insulation but the heat loss to the ambient environment will still occur.

3.8 Condensation and water effects to the Thermoelectric Generator

Care must be taken as with any other electrical device, not to immerse the TE Collar while under power. This device should always be dry when in use to prevent thermal and electrical shorting. "Once water is condensed inside the module, the water molecules are held together in long chains due to an effect called Van der Waals bonding. These are the same bonds that give liquid water its surface tension. In liquid form, the long chains of water molecules are too big to fit through the spaces in between the silicone rubber molecules. This permeability to water vapour and impermeability to liquid water is a recipe for disaster [5]"

Over time, the so-called "sealant" acts like a water pump, since water vapour gets in and the liquid water cannot get out. The consequence is corrosion and even electrical shorting as water dissolves the salt residue left behind from the assembly fluxes. The final result will be gradually degrading cooling performance ultimately resulting in catastrophic failure.

To ensure sweating (from the skin) and condensation do not effect the operation of the TE Collar sealant is provided.

1. Epoxy Sealing (EP) - A (lightweight), syntactic foam epoxy resin for electronic encapsulation and perimeter sealing. When cured the material is completely uni-cellular and therefore the moisture absorption is negligible. The material exhibits a low dielectric constant, low coefficient of thermal expansion and low cure shrinkage. It contains micro balloons to reduce thermal conductance. Usable temperature range is -40 to +130˚C. This is the best application for TEM water sealant.
2. Silicone (RTV) - A perimeter seal that retains elastomeric properties over a wide temperature range. This non-corrosive material exhibits excellent electrical properties, UV, chemical and weather resistance. Usable temperature range is -60 to +204˚C. Silicone materials, in particular, are not highly cross-linked: on a microscopic level, there are large spaces in between the long chains of silicone rubber molecules. These spaces are large enough to allow water vapour molecules to pass through. It is the least effective against moisture protection as the material blocks the water vapour from leaving the TEM.
3. Conformal Coating (EC) - Conformal coating is a transparent, general purpose dip epoxide surface coating that is used for coating electronic components for corrosion protection and high insulation resistance. It is however not a perimeter seal. Can be used in conjunction with RTV. Usable temperature range is -55 to +150˚C. this sealant is inferior to epoxy sealing.
4. Acrylics
5. Potting- A perimeter sealant with a highly cross-link molecules to prevent diffusion of water vapour to the inside of the module.

There is always some small degradation in performance when a module is sealed because the sealant conducts some heat from the hot side of the TE module to the cold side of the TE module. This will happen regardless of the type of sealant compound that is used.

3.9 Background and Theory

The atoms and molecules that compose the MPTG materials are in constant motion, and the interactions among them produce displacements in the elementary charges within them. The resulting accelerating charges and changing electrical dipole moments produce thermal radiation.

A thermopile is made of thermocouple junction pairs connected electrically in series. The absorption of heat by one of the thermocouple junctions, called the active junction, increases its temperature. The differential temperature (ΔT) or temperature gradient between the active junction (hot side) and a reference junction (cold side) temperature produces an electromotive force directly proportional to the differential temperature created. This effect is called a thermoelectric effect.

The concepts of thermoelectricity are based on thermoelectric effects and solid-state physics.

3.9.1 The thermoelectric effects

The phenomenon involving an inter-conversion of heat and electrical energy may be termed a thermoelectric effect and differentiated between reversible and irreversible energy conversion. The best-known irreversible thermoelectric effect is the Joule effect, where an electric current 'I' in ampere is transformed irreversibly into heat 'P' measured in Watt, according to:

$$P = I^2 R \tag{3.13}$$

where 'R' is the electrical resistance of the conductor in ohm. The Seebeck, Peltier and Thomson effects are three related reversible thermoelectric effects where the Seebeck effect is the principle in governing thermopile operation.

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

$$E_{AB} = \Delta T\, S_{AB} \tag{3.14}$$

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

Jean Charles Athanase Peltier (1785-1845) discovered that when an electric current flows across a junction of two dissimilar metals, heat is liberated or absorbed depending on the direction of the electric Seebeck current. The Peltier coefficient is the reversible thermal change when one coulomb crosses a junction. The rate of heat liberated or absorbed P(W) is proportional to the electric current I(A) flowing in the conductor, that is:

$$P = P_{AB}(T)\ I \qquad (3.15)$$

where

$$P_{AB} = (P_A - P_B) \qquad (3.16)$$

where 'P_{AB}' in volt, called the relative Peltier coefficient. This effect is the basis of thermoelectric refrigeration or heating.

Thomson discovered that if an electric current flows along a single conductor while a temperature gradient exists in the conductor, an energy interaction takes place in which power is either absorbed or rejected, depending on the relative direction of the current and gradient. More specifically heat is liberated if an electric current flows in the same direction as the heat flows; otherwise it is absorbed. The power 'P'' absorbed or rejected per unit length (W/m) is proportional to the product of the electric current 'I' and the temperature gradient dT/dx (K/m), giving:

$$P' = \beta\ I\ dT/dx \qquad (3.17)$$

where β (in V/K) is the Thomson coefficient and the specific heat of electricity.

3.8.2 Thermodynamics of thermoelectricity

The thermodynamic relationships involving the three reversible thermoelectric effects (Peltier, Seebeck and Thomson) are vital for understanding due to the quantum mechanics involved. The thermodynamic theories presented are essentially from the work of Daniel Pollock [1 & 12]. Let us consider a thermoelectric circuit where Joule heating is neglected. If a closed circuit constitute of two dissimilar conductors A and B in which the cold junction is at 'T' and the hot junction at 'T + ΔT'. If the emf generated or RSE in this circuit is E_{AB} (V), the thermoelectric power is defined as the change in emf per Kelvin, dT/dE_{AB} (V/K), such that the electrical voltage given by [1 & 12].

$$I\ E_{AB} = I\ dE_{AB}/dT\ \Delta T \qquad (3.18)$$

And for the unit current flow

$$E_{AB} = dE_{AB}/dT\ \Delta T \qquad (3.19)$$

It should be noted that although dE_{AB}/dT is called the thermoelectric *power* its dimensions are not power (W) but volts per Kelvin (V/K). Taking into account the heat absorbed and liberated at the junctions (Peltier effects) and the heat absorbed and liberated within the conductors (Thomson effects), the conservation of energy in the system, considered as a reversible heat engine, in which a current I (A) flows, can be written as

$$dE_{AB}/dT\ \Delta T = \pi_{AB}\ (T + \Delta T) - \pi_{AB}(T) + (\beta_B - \beta_A)\ \Delta T \qquad (3.20)$$

where 'π' and 'β' are the Peltier and Thomson coefficients and:

Peltier effects at junction:
Heat absorbed at hot junction = π_{AB} (T + ΔT)
Heat liberated at cold junction = π_{AB} (T)

Thomson effects from the conductors:
Heat absorbed in conductor = β_B (ΔT)
Heat liberated in conductor = β_A (ΔT)

If we simplify Equation 3.20 by dividing through by 'ΔT' and then taking the limit as 'ΔT' approaches zero, we obtain the fundamental theorem of thermoelectricity,

$$dE_{AB}/dT = d\pi_{AB}/dT + (\beta_B - \beta_A) \qquad (3.21)$$

This equation, which is homogeneous in V/K, gives the electrical Seebeck effect as the sum of the thermal Peltier and Thomson effects. This proves the relationship between the three effects and is the basis of the statement that the **Seebeck effect is the result of both the Peltier and Thomson effects** according to Pollock [1&12]. The thermoelectric power is the algebraic sum of the absolute thermoelectric powers of its components. The Relative Seebeck Coefficients (RSC) of the Thomson effects are due to the potential difference Absolute Seebeck Effect (ASE) that exists in each of the thermoelements of the thermocouple when a temperature gradient is present in open circuits. The open circuit RSC of a thermocouple is therefore:

$$dE_{AB}/dT = \alpha_A - \alpha_B \qquad (3.22)$$

where the Absolute Seebeck Coefficients (ASC) of each of the components of the thermocouple materials, or thermoelements are α_A and α_B The concept of the ASC is very important because it allows the study of the properties of individual thermoelements. If the ASC of one thermoelement is known and the thermoelectric power of the couple is determined experimentally, the ASC of the unknown element can be calculated using Equation 3.22.

The integrals of the Seebeck coefficients are the absolute Seebeck effects. The flow of current in this circuit is induced by the Relative Seebeck Coefficient (RSE) as a consequence of the temperature difference between the two junctions of conductors A and B. Because the Thomson effect is present only when a current passes along the conductor, the Thomson coefficients (β_A and β_B) are nonzero only in closed circuits. This means that Equation 3.21 can account for thermoelectric properties only in a closed circuit. In contrast to this, the electrical potential (emf) within conductors is always present as long as a temperature difference is maintained between the two junctions, regardless of whether the circuit is open or closed. Hence, Equations 3.22 is valid for both open and closed circuits. Usually the RSE is measured in open circuits to eliminate the Thomson and Peltier effects, which cause extraneous thermal variations [1&12].

The three laws of thermoelectric circuits may be inferred:
(1) The law of homogeneous conductors;
(2) The law of intermediate conductors; and
(3) The law of successive temperatures.

The law of homogeneous conductors states that; a thermoelectric current cannot be maintained solely by application of heat to a single homogeneous conductor, regardless of any cross-sectional variations. This means that a thermoelectric circuit is formed of two conductors of the same homogeneous material ($S_A = S_B$), no emf exists in this circuit. The law of intermediate conductors states that the sum of the absolute Seebeck coefficients of dissimilar conductors is zero when no temperature difference exists between the junctions. In other words no extraneous emf will be produced in a circuit made of intermediate materials if no temperature differences exist between the two ends of the materials. This law demonstrates that the contribution of a common thermoelement C to a pair of thermoelements A and B vanishes if the junctions A-C and C-B are at the same temperature.

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

$$E_{AB} = \int_{T0}^{T3} (\alpha_A - \alpha_B)\, dT \qquad (3.23)$$

With Equation 3.23, the influence of circuitry and extension wires can also be expressed in thermoelectric thermometry.

3.8.3 Solid State of thermoelectric effects

Thermodynamics provides a means but not the model for thermoelectric properties. The required model follows from an understanding of the roles of electrons in thermoelectric behavior. The relative Seebeck emf produced in a thermoelectric circuit (RSE) has no relationship with contact potential, or Volta effect. The contact potential is measured by the difference in work functions when two different metals are brought sufficiently close so that electron transfer creates a common Fermi level in both metals. This does not require a temperature difference and for closed circuits the net voltage is zero.

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

Seebeck current flows easily is the junction maintained at the higher temperature and thus the current absorbs heat in an effort to cool the junction to the equilibrium temperature.

At the other junction the Seebeck current has to go against the electric field, thus having to do work heating up the junction in an effort to bring the temperature up to the equilibrium temperature. The emphasis is placed on the fact that the Seebeck effect is only dependent on the temperature difference between the two junctions made of dissimilar and homogeneous conductors. It does not depend on the junction cross-section or the temperature distribution like the temperature gradient inside the conductors. This hypothesis is known as the Magnus law. Isotropy and homogeneity of the metal forming the conductors is a requirement of this law. However, because there are stresses and strains in any solid metal in which there is a temperature gradient, the universal applicability of the law must be called into question. Even with the qualification that the metal be isotropic and free from stress, there is not unanimous acceptance of this law.

There is a possibility of the existence of other thermoelectric effects not generally taken into account. Among these thermoelectric effects is a 'homogeneous thermoelectric effect,' which is a temperature difference in the steady state between the ends of a long uniform wire carrying a steady current. These effects are generally considered to be sufficiently small to be neglected [1].

3.10 Motivation for the choice of a thermoelectric device

The main goal of this research is to develop a thermal generator capable of developing voltage to be used on compact equipment. The motivations for replacing the current usage of dry cell batteries is that with thermopiles it is possible to generate enough power to self-power compact equipment with body heat. The use of Peltier devices is commercially available and the efficiency in waste heat applications not a major consideration. According to Buist[8], TE modules are manufactured form materials of high efficiencies at nominal temperatures. Therefore, these TE modules represent the highest efficiency devices that can be used as thermoelectric power generators at low intensive energy sources.

The dependencies in remote areas on batteries and a reliable power source are omitted. Independency is a major consideration when looking for energy sources. It is also a cost exercise and has a calculated payback time of less than 5 years; the TE Collar is well worth those considerations. The practical implication of these devices in a work environment, like mines, oilrigs, farms, commercial and industrial plants are endless. Considerations include the effect on healthcare devices, heart pagers, constant body monitoring devices not to mention the military advantage of these devices to the common soldier as reflected in the above quote from NASA in the beginning of this chapter.

3.11 The thermopile thermal model

The one-junction-pair thermopile is considered as a lumped system. The heat exchanges with the external environment are the heat input, that is the radiant energy incident to the detector (at T), and the heat losses through conduction to the heat sink and radiation to the surroundings (at T_a). It is assumed that the temperature of the absorbing layer of the thermopile is near the ambient temperature and that the heat loss through radiation can be neglected.

Power output from a thermopile is approximately proportional to the area and inversely proportional to its length. Large number of voltage with a low wattage and a reasonable efficiency can be obtained through the usage of thermocouples with thermoelements that posses an extreme ratio of length-to-cross-section-area. The conventional thermocouples are low-voltage, high current devices and the requirement to generate high power, allow the thermocouple to be connected electrically in series or parallel or both to form the module.

3.12 Parameters available to improve the device power efficiency

The dimensions, the conductivity, and the geometry of the Peltier devices are parameters available for improving the power output of the device. This implies the need for a compromise between the power output and optimization of Peltier devices. To summarize, the parameters, which could be used to improve the MPTG performance, are:

1. The thermal resistance layer material and its geometry;
2. The dimension of the gap between the active and the reference junctions;
3. The thickness of the absorber layer;
4. Insulation material between TEMs;
5. Insulation material between heat and cold sink;
6. The length of the thermoelements;
7. Reduction of the ceramic plate thickness; and
8. Improving thermal contacts and properties

3.13 Thermoelectric Generators (TEG)

In the following section a brief historical review of the development of thermoelectric generators is given along with a survey of different types of commercial units and their applications. This survey, however, is limited. It is necessary to discuss these applications and some of the related issues. Especially it is hoped to explore the use of MPTG as a thermoelectric generator in the future.

The commercial usage of TEG became available in the 1960's. The reason for the usage of TEGs in the industry across the world is due to; high reliability, minimum number of moving parts, long interval schedule of service and or maintenance and long life. Usually minimum part replacement is required even after 30 years of continuous operation [13]. Mostly gaseous fuel such as propane or natural gas, or liquid fuels such as petrol or diesel power the generators. They are classified as gas-fuelled or liquid-fuelled generators.

3.13.1 Miniature Power Generators and Medical Implants

Miniature Power Generators consist of a large number of thermopiles connected electrically in series to a form a module. The generators employ radioactive materials as a heat source in a monolithic structure. The devices are geometrically arranged around the heat source to optimise the configuration and for mechanical strength.

The application of monolithic thermoelectric generators for military and naval use was of such a nature due to their power output that the development did not fall into this category. However, the application for these devices found widespread acceptance in medical cybernetic devices and stimulators, which require only milliwatt power generation. Nuclear-powered thermoelectric batteries for pacemakers were first implanted in April 1970 in the Broussais Hospital in Paris France. The next phase include thermocouples utilizing internal body heat as per recent news article below.

Body heat could power the next generation of heart pacemakers

John von Radowitz
in London

PACEMAKERS and other life-saving implants could in future run on body heat, it was claimed yesterday.

New York-based Biophan Technologies is developing a "biothermal battery" that uses the warmth of a patient's body to generate electricity.

One of the biggest drawbacks of pacemakers and implantable defibrillators is that every few years patients must undergo surgery to replace their batteries.

The biothermal battery could make such operations unnecessary. The battery employs thousands of thermoelectric generators built into an implant, 'New Scientist' magazine reported.

These exploit the well-known thermocouple effect in which a small voltage is generated whe the junctions of two dissimilar materials are ke at different temperature

The device would be planted just below the skin where there can be temperature difference o as much as 5C..

Figure 3.6 Newspaper Article from Irish Independent, June 2004

3.13.2 Data Gathering

In data gathering, TEGs have been widely accepted in a variety of data gathering equipment. This equipment is either continuous or intermittently transmitted by radio to a central site. The power requirement of systems referred to as SCADA (Supervisory Control and Data Acquisition) vary from below 100W. They are usually mounted or installed on pipelines as pipeline metering stations, monitoring the flow, or as telemetry stations for water distribution.

3.13.3 Cathodic Protection

Cathodic protection is the use of electrical current to prevent metal corrosion to structures. These TEGs are normally used at gas wells and pipelines to protect the casings. For cathodic protection, a high current low-wattage is required which suits the TE ideally. The requirement ranges form 60W and higher. The natural gas from the well or pipe is used to supply the fuel to the generator.

3.13.4 Telecommunications

TEGs are used to power microwave, VHF, cellular, television, commercial radio and two-way radio repeaters. These repeaters are usually located in isolated spots or on high mountains or hills where the normal power grid is not available. These TEGs are fuelled by bottled propane gas and possibly, due to the expense of delivery, the fuel consumption is a major issue. Therefore, the application of TEGs as the best energy converter in these remote conditions.

3.13.5 Combination Heater Generator

TEGs generate a huge amount of heat in comparison to the electricity produced. In many applications, sensitive electronic equipment must be kept at certain temperatures in cold environments. This equipment is heated by the waste heat from the TEGs and generated at the same time the electricity required to power the same equipment. They are referred to in the industry as self powered heaters.

3.13.6 Modular Radioisotope Thermoelectric Generator (RTG) Technology

Weather stations, navigational aids, sub-sea operations, terrestrial applications and space power all utilise RTG as the principle power generation device [14]. Some of these applications utilise the heat generated form the thermopiles as well as form equipment to enhance performance. Due to the long and reliable life guaranteed by RTGs, they are very popular in technology usage. The RTG utilise ^{238}Pu oxide fuel pellets for each thermoelectric module. At the beginning of the module 'life' the designed thermal energy is about 250W per module. Per pellet 62.5W is generated. Each of these pellets is encapsulated in a vented iridium cladding. This cladding provides the primary containment of these fuel pellets and additional Graphite Impact Shell (GIS) for added impact protection.

The thermoelectric multicouple device converts the thermal energy from the isotope heat source to usable energy. It consists basically of a graphic heat collector, thermoelectric couples electrically connected in series, graphite cold cushion and a tungsten-mounted stud for attachment to the outer shell. Research is currently underway to improve the efficiency and materials figure-of-merit (z) used via modifications on dopant concentrations as well as nanophase materials to increase scattering of photons [14].

3.13.7 Hazardous-area Generators

TEG are widely accepted in hazardous environments where TEGs can operate in explosive atmospheres like oil and gas fields or locations where an ignition may spark or ignite the gasses. These areas typically include metering stations as well.

The use of thermopiles as sensors and detectors is omitted, as this discussion is beyond the scope of this thesis.

3.14 Conclusion

TE technology is delicate in nature; there are multiple factors to consider in arriving at a suitable solution to generate electricity through this technology. With this aim in mind, a necessary balance of cost must be calculated and with this cost the feasibility of proceeding (see Chapter 7). Unfortunately, cost is the most constraining force in using any technology and therefore the onus rests upon the individual (researcher) to focus on what the real aspiration and issues are and if the concept implementation is viable.

Chapter 4- Elemental Thermoelectric Materials and Construction

4.1 Introduction

Group	**1**	**2**		**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanthanoids			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Actinoids			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Figure 4.1 Periodic Table of the elements

For a good semiconductor material, highlighted in Figure 4.1 above, the criteria in thermoelectric power generation at ambient and above temperatures would be the following considerations:

1. 'High crystal symmetry with electronic bands near Fermi level.
2. Heavy element compounds with small electro-negativity difference between the constituent elements.
3. An energy gap of approximate 10 $\sigma_B T$, where T is the temperature of operation and σ_B the Boltzmann's constant [1]'.

4.2 Transport of Heat and Electricity in Crystalline Solids

According to electron theory, electricity is the movement of electrons in a circuit when there is a continuous conductive path across an applied voltage. The voltage provides an electromotive force (emf) setting the electrons into motion. The resulting electrical current is measured in terms of the number of electrons moving past a given point in one second, where one ampere equals the movement of electrons (6.25×10^{18}) per second.

Charge carriers are the physical components of a material that allow it to conduct electricity. The precise nature of these carriers is a function of the material's atomic structure. The fewer the number of electrons in an element's outer shell, the more freely or loosely it bound to the atom's nucleus, and the easier it is to make it flow with the application of a voltage.

Semiconductor materials are 'grown' into crystalline structures with given conductive properties by adding (or dopant) impurities. In their purest form the base semiconductor materials form crystalline lattices which, when sharing electrons among the constituent atoms become very stable. The electrons are in constant motion as they orbit the nuclei in the lattice. The shared electrons, however, are continually pulled into the orbits of adjacent nuclei to maintain the structural stability of the lattice. In this pure state, the material is not highly conductive.

Once impurities are added, the conductive properties are radically affected. 'Free' or valence electrons are created which do not fit into the crystalline structure or type of bonding of the semiconductor. The extra electron consists of a negative charge in the lattice loosely associated with the impurity ion. These electrons are thus 'loosely bound' and when a voltage is applied, they can be easily set into motion to allow electrical current to pass. The loosely bound electrons are considered the charge carriers in this 'negatively doped' material referred to as 'N' type material and the ions referred to as donors because of the contribution of electrons in the conduction process. The usages of electrons as charge carriers in conductors are part of the property of a given material.

If impurities are added having one less valence electron, a more conductive crystal is formed. This crystalline structure has 'holes' where normally within the crystal an electron would be found if the material was pure. This induces a positive charge on the ion and acts as a potential hole to nearby electrons from ions. These 'holes' increase electron flow through the material when heat or voltage is applied. The motion of the hole transfers the ion from one to another in the valence band. These 'holes' are considered to be the charge carriers as a result of positive 'holes' in this positively doped conductor referred to as 'P' type material. 'P' material can only be fabricated within crystalline structures.

In the MPTG application, these charge carriers can be set or forced into motion via the flow of heat or thermal energy and will cause electrical voltage and current to flow, assuming a complete circuit. When connecting an electrical conductor between two different temperatures, the conductor is capable of transferring thermal energy from the warmer side to the colder or across the temperature gradient. The physical process of transferring the heat or temperature difference, move the electrical charge carriers within the conductor in the same direction as the heat. This charge carrier movement generates electrical current in MPTGs.

To ensure this principle works, the conductor, which completes the circuit, must not be identical to the first conductor. If two similar conductors are applied, the flow of thermal energy will create a potential for equal charge carrier movement in both these conductors and the potential for current flow in one conductor is in complete opposition to the other conductor, result in the cancellation of each net current flow.

To comply with the Seebeck effect, two dissimilar conductors are used. The different capacities for moving charge carriers in response to thermal flow, the current level in one conductor will overcome or complement the potential for thermally-generated current flow in the other conductor. The net effect is a continuous current level equal to the generated current capacity of the primary conductor (for that given temperature difference) minus the generated current capacity of the second conductor [5]. The existence of this net current flow indicates that a voltage is created through the movement of heat. The voltage generated is referred to as Seebeck voltage.

Probably the most well known example of this phenomenon is the common thermocouple (refer to Table 1.1). The voltage generated by a thermocouple is a function of:

1. The temperature difference (ΔT) between the two thermocouple junctions, and
2. the properties of the conductors used.

Thermocouples are used primarily for temperature measurement—not power generation. Thermoelectric power generation (TEG) devices typically use special semiconductor materials optimised to utilise the Seebeck effect.

4.2.1 Movement in N-Doped Pellets

Heat moves from the hot to the cold side of the pellet, the charge carriers or electrons from the dopants are carried with the heat flow in the direction of charge carrier movement. Heat also effects the charge carrier movement in the return path. Due to the heat flow carrying more charge carriers in the semiconductor material than in the circuit return path, a significant potential difference is generated. Electrons are repelled by the negative pole or hot side and attracted by the positive pole or cold side (see Figure 4.2). This forces the electron flow in a clockwise direction. With the electrons flowing through the N-type material from bottom to top, heat is absorbed at the bottom junction and actively transferred to the top junction. The charge carriers through the semiconductor pellet effectively pump this heat.

4.2.2 Movement in P-Doped Pellets

In thermoelectric power generation, 'P' pellets hole flow is in the opposite direction of electron flow. These 'holes' enhance the electrical conductivity of the P-type crystalline structure, allowing electrons to flow more freely through the material when a heat or voltage is applied. Positive charge carriers are repelled by the positive pole of the hot side and attracted to the negative pole or the cold side (see Figure 4.2). Because the charge carriers inherent in the material are conveying the heat through the conductor, use of P-type materials results in heat being drawn toward the negative pole (cold side) and away from the positive pole (hot side). This contrasting heat-pumping action of P and N-type materials enhance TEG capabilities and voltage generation as both compliment each other in the same direction of charge carrier movement.

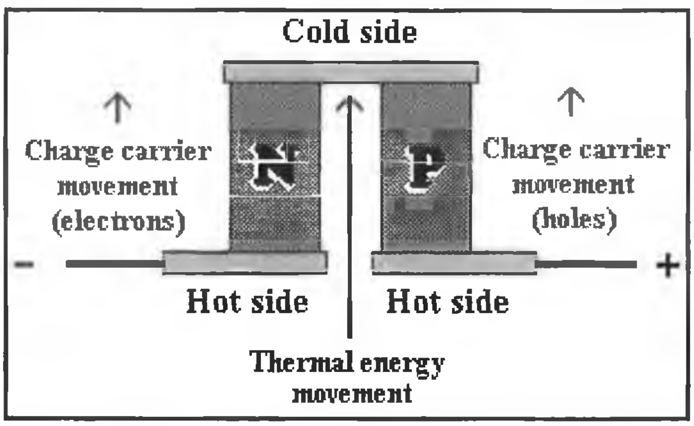


Figure 4.2 Single N- and P Doped Pellets in Series Electrical and Parallel Thermal [5].

4.2.3 Movement in Multiple Combined N and P-Doped Pellets

Through the use of both N and P type materials in a single power generation device, the Seebeck effect is optimised. As shown in Figure 4.3, the N and P pellets are configured thermally in parallel, but electrically in a series. Because electrical current or electrons flow in the opposite direction to hole flow, the current generating potentials in the pellets do not oppose one another, but are series-aiding. Therefore, each pellet develops a Seebeck voltage in combination of an N and P pellet would generate approximately double the voltage. By arranging N and P-type pellets in a 'couple' and forming a junction between them with a plated copper conductive strip, it is possible to configure a series circuit keeping all of the heat moving in the same direction. In the MPTG application, N and P couples will enhance the Seebeck voltage to useful levels.

Another possibility is to connect the N and P pellets to a pellet-to-pellet arrangement or a zigzag connection to achieve a series circuit. These interconnections however, produce thermal shorting that significantly compromises the performance of the TE devices.

Figure 4.3 illustrates the end of the P-type pellet connected to the positive voltage potential and the end of the N-type pellet similarly connected to the negative side of the voltage. The positive charge carriers in the P material are repelled by the positive voltage potential and attracted by the negative pole or cold side. In the N material, the negative charge carriers or electrons are likewise repelled by the negative potential and attracted by the positive pole of the hot side. In the copper plates and wiring, electrons are the charge carriers; when these electrons reach the P material, flow through the 'holes' within the crystalline structure of the P-type pellet occurs. Electrons flow continuously from the negative pole of the hot side, through the N pellet, through the copper tab junction, through the P pellet, and back to the positive pole. Because of the usage of two dissimilar types of semiconductor material, the charge carriers and heat are all flowing in the same direction through the pellets as indicated by the thermal flow in Figure 4.3.

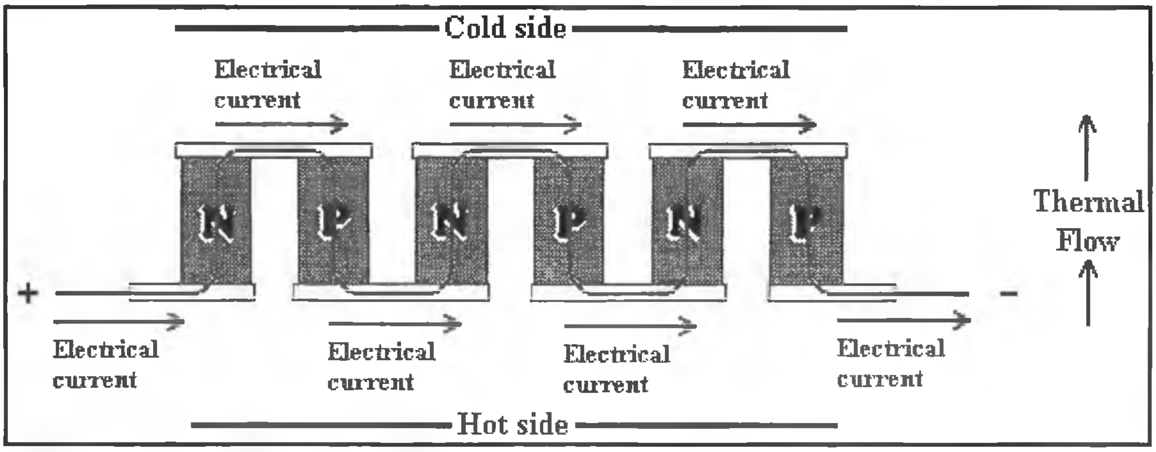


Figure 4.3 Combination of Multiple N- and P Doped Pellets in Series Electrical and Parallel Thermal [5].

With the increase in temperature at the hot side, the carriers in each pellet will diffuse to the colder portion or cold side in order to lower their potential energies. The heat is absorbed at the hot side and liberated at the cold side, creating the Seebeck current as indicated Figure 4.3 above.

By combining TE couples, it is possible to band pellets together in rectangular arrays to create thermoelectric modules (refer to Figure 1.1). A typical Seebeck (Peltier Cooling device) module would have 127 N and P couples (or 254 N and P pellets). This gives a greater heat-pumping capacity. The semiconductor couples are wired in series and thermally in parallel to pump the heat together in the same direction. Therefore, TE devices are also suitable and widely used in commonly available DC power supplies.

Without a depletion region, a TE couple will conduct in both electrical polarities with no fixed voltage drop across the couple. In fabricating devices with multi-pellet arrays, a means is required to mechanically hold everything together. A solution is to mount the conductive tabs to thin ceramic substrates or aluminium. The outer faces of the ceramics are then used as the thermal interface between the Peltier device and the hot or cold side. Ceramic materials have become the industry standard for this purpose because they represent the best compromise between mechanical strength, electrical resistivity, and thermal conductivity [5].

4.3 Materials for Thermoelectric Generators

The temperature difference or gradient in every material leads to an irreversible flow of heat that opposes that temperature gradient [1]. In the absence of electric current, the thermal conductivity 'κ' may be explained as:

$$\kappa = w\,(dT/ds)^{-1} \qquad (4.1)$$

where 'w' is the heat conduction per unit area. If the heat flow is in the same direction as electrical current due to the Seebeck effect, the Peltier effect will oppose the temperature gradient. According to the reversible Thomson effect, heat is absorbed or liberated equivalent to the emf and current changes along the temperature gradient, therefore the thermal changes in the conductor are the equivalents of the electrical outputs.

Thermal conduction and heat are two irreversible processes that work against each other to lower than the thermodynamic limit. Therefore thermoelectric materials must combine a large Seebeck coefficient 'α' with a low electrical resistivity 'ρ_e' and thermal conductivity 'κ'.

The most desirable material should have a high Boltzmann's constant 'σ_B' and low thermal conductivity 'κ'. The Boltzmann's constant is statistics on the classical kinetic theory of gasses (the gas constant R divided by Avogadro's number N_A) based on energy in a metal assumed to be constant and lower than that required to leave the metal [11]. This is one of the foundations for considering the electron to be in a potential well. The Joule effect (Equation 2.13) represents the loss in power in electrical generation. Therefore, the thermodynamic efficiencies are decreased resulting 'κ' to allow heat flow to the heat sinks and reduce the 'ΔT' due to heat losses at the heated side. Finding the best balance in combination of 'S', 'σ_B' and 'κ' is required for materials in electrogeneration applications in order to create the best efficiencies. The figure of merit, 'Z', is applicable to describe the materials property requirements.

$$Z = S^2\sigma_B/\kappa = S^2/\rho_e\kappa \qquad (4.2)$$

where:

ρ_e Material Resistivity
κ Material Thermal Conductivity
S Absolute Thermoelectric Power
σ_B Boltzmann's constant (1.4×10^{-23} J/K)

The thermoelectric power 'S' of a semiconductor depends on the amount of dopant present, the energy levels of the dopant, the energy gap and the temperature. These factors determine the amount of carriers per unit volume and thus influence the electrical conductivity [2].

Material	Electrical Resistivity ρ_e (Ωm)	Seebeck Coefficient α (μV/K)	Figure of Merit Z (K^{-1})	Reference
Si	3.5×10^{-5}	450	4.0×10^{-5}	a
Positive thermoelements				
ZnSb			1.0×10^{-3}	b
PbTe			$<1.2 \times 10^{-3}$	b
PbSe			$<1.2 \times 10^{-3}$	b
Sb_2Te_3	5.0×10^{-6}	+130	1.2×10^{-3}	b
Bi_2Te_3		+190	1.8×10^{-3}	b
Ge (thin film)	8.3×10^{-4}	+420	3.3×10^{-6}	c
InAs	2.0×10^{-5}	+200	8.0×10^{-5}	d, e
Bi_2Te_3	1.2×10^{-5}		2.2×10^{-3}	f
$Bi_2Te_3 - 25\%Bi_2Se_3$			2.7×10^{-3}	f
$Bi_2Te_3 - 10\%Bi_2Se_3$			2.8×10^{-3}	f
Negative thermoelements				
PbTe	7.7×10^{-6}		1.5×10^{-3}	b
Bi_2Te_3		-210	2.3×10^{-3}	b
Ge (thin film)	6.9×10^{-3}	-548	6.8×10^{-7}	c
InAs	2.0×10^{-5}	-180	2.7×10^{-5}	d, e
$InP_{0.1}As_{0.9}$			6.0×10^{-4}	d
Bi_2Te_3	8.2×10^{-6}		2.6×10^{-3}	f
$Bi_2Te_3 - 25\%Sb_2Te_3$			2.2×10^{-3}	f
$Bi_2Te_3 - 50\%Sb_2Te_3$			2.8×10^{-3}	f
$Bi_2Te_3 - 74\%Sb_2Te_3$			3.0×10^{-3}	f

a Van Herwaarden, A. W., The Seebeck effect in silicon IC's, Sensors Actuators, 6, 245, 1984.
b Goldsmid, H. J., Applications of Thermoelectricity, Butler and Tanner, London, 1960.
c Onuma, Y., Thermoelectric power of a vacuum deposited germanium thin film, Electr. Eng. in Jpn., 89,72,1969.
d Kekelidge, N.P., Kuindadze, Z. N., Davitaya, Z. F., Eritayan, G. N., Saakyan, V. A., and Karapetya, E. K., Studies of thermoelectric characteristics of InP^Asi.x alloys, Phys. Status Solidi A, 38, K49, 1976.
e Hocking, E. F. et al., Thermal and electrical transport in InAs-GaAs alloys, J. Appl. Phys., 37, 2879, 1966.
f Heikes, R. R. and Ure, R. W., Thermoelectricity, Science and Engineering, Interscience Publishers, New York, 1961.

Table 4.1 The Figure-of-Merit of some Thermoelectric Materials [4]

Finding a higher Z value will increase the thermal efficiency. With new materials, quantum well confinement, superlattice and or nanowires structures, enhance Z values above the normal 5% are now possible [3].

Due to the low heat gradient and the temperature difference, it is feasible to utilise semiconductor TE refrigeration modules for the MPTG application. The bismuth telluride (Bi_2Te_3) with space group 'D^5_{3d}' is used for the material of choice for producing the Peltier effect. They are simply and easily optimised for pumping heat and control of the type of charge carrier employed within the conductor.

'For any given material, '*ZT*' for optimum doping usually rises with temperature until it is no longer possible to prevent two-carrier conduction. Eventually, certain materials also become chemically unstable as the temperature is raised, even though it may not be close to melting point' [1]. Bi/Sn solder melting point is at approximate 138˚C. For this reason, Bi_2Te_3 and similar alloys are not suitable for applications at temperatures higher than 400K (127˚C). To accommodate this, lead based telluride may be used for higher temperatures or silicon alloys with germanium.

4.4 Design of TE Modules

For the low intensity power generation, single stage Pettier (Cooling Devices) type TM-TE-63-1.0-2.5P Thermoelectric Module (Potted) were chosen, manufactured by TE Technology Ltd. The dimensions of the TEMs are 30mm(L) x 15mm (W) x 3mm (D). The Peltier devices are ideally suited since they are specifically fabricated from the highest performance materials available for the operating temperature range of the TE Collar. However, TEMs with a higher ΔT_{max}, would generate proportionally higher power.

The AC resistance of the modules selected is 3.3Ω at 27˚C. Each of the modules thermal conductivity 'κ' is approximately 0.9 W/m/K at 27˚C. The Peltier TEMs were selected due to their high 'efficiency' at small ΔT's typical required for the TE Collar design and application. TEMs used for industrial generation operates at higher temperatures outside the temperature range of this study and require a different material assembly such as alloys PhTe and Si/Ge. The pellets for the Peltier devices incorporate alloys such as Bi, Sb, Te and Se amounts to make the Bi_2Te_3 N- & P-type material.

Another reason for choosing these TEMs was to keep the height of the TE Collar to a minimum (about 30mm). This is to keep the neck movement to maximum without causing too much restrictions of the immovable TE Collar. Due to the circumference, the width required is to be minimal in order to achieve contact with the TE Collar outer band and to ensure the bending curve must stay in contact between the Collar surface and skin area (see Figure 3.2 & 3.3).

For future considerations, losses may be reduced in smaller type of TEMs via increased contact with the heat and cold sinks. Another consideration would be to omit certain restricting materials in the construction process and incorporate the heatsinks directly to the TEM surface. This would be addressed in more detail in Chapter 9.

The total coverage area for the TEM on the TE Collar is 0.00765m^2 (17 TEMs in total). The TE Collar aluminium band dimensions as constructed, is approximate 400mm(L)x30mm(W)x1mm(D) and cover a skin area on the neck of less than 0.012m^2. This gives the aspect ratio between the area of the band and TEM modules in contact with the skin of 63.75%. The rest of the area, 36.25% is covered in thermal insulation, to reduce the heat transfer from the skin to the heatsinks. This increases the efficiencies as the heat is transferred via the TEMs only, apart from some radiation and convection losses. The outside of the collar is also coated white to reflect heat away from the collar.

4.5 Heat Transfer in TE Modules and Associated Complications

Special requirements are needed on the hot side temperature of the TE device in order not to exceed the melting temperature of the solder employed to secure the semiconductor pellets to the copper tabs. Temperature damage reduces the operation life and performance of the TE Modules considerable. It is recommended that the temperature be kept below 200°C (some manufactures even require the temperature to be as low as 140°C). Toward this end, it is a good practice to use some type of 'heat spreader' to prevent hot spots at the hot-side module interface. Generally, this means employing a relatively thick casting or extrusion between the heat source and the module.

On the mechanical side—especially when using multiple devices— the requirement to find a means of applying compression between the hot and cold sides, which will apply even pressure across the modules and, most importantly, prevent the hot-side interface from bowing. If there is too great an expanse between compression points, the hot side interface can distort to the point where some modules are crushed or the thermal interface is compromised.

The lead wires for the TE modules as supplied by TE Technology Ltd incorporate 58/42 bismuth/tin solder with a melting point of 138°C. The solder used to connect the lead is the normal electronic lead/tin solder with a melting point of 180°C. This mixing of solder types yields inconsistent and detrimental solder properties directly affecting the performance of the TE Collar.

Thermal insulation is required to reduce the thermal bridge or carry-over from the hot side to the cold side outside the TEM thermal path. In the construction of the TE Collar, 'Hot Melt Glue' was used to form a primitive insulation between the TEMs and the aluminium band. The glue was applied via a 'Glue Gun' with a working temperature of 170°C.

4.6 Heat Transfer and the use of Heatsinks

4.6.1 Effect of Heat on Heatsinks and Thermal Path

In TEM power generation, no system is complete without a means of heat sinking or dissipating of the waste heat from the cold side. In the TE Collar, the TEMs absorbed the heat from the cold sinks (or directly) and dissipated it into the ambient environment via the heat sinks. For the maximum output power, the temperature rise at the base of the TEMs must be held at the maximum. As the base temperature rises at the cold sink or base, additional output power is released and the heat sink (see Figure 3.5) requires more temperature or heat to be released into the environment.

The TE Collar total heat load consist of the sum of the heat loads that effect the TEMs surface. This includes the surface area that protrudes around the TEMs that's not in touch with the body skin surface. The individual heat loads to the TE Collar consist of the following:

1. The conductive load from the body skin temperature to the TEMs;
2. The radiation load via infrared wavelengths;
3. The convection load to the ambient environment; and
4. The electrical power dissipates by the TE Collar.

Material	**Thermal Conductance**	**Electrical Insulator**	**Thermal Resistance (°C/W)**	**Other Properties**
Mica	Good	Excellent	~ 0.75 - 1.0	Fragile
Kapton	Good	Excellent	~ 0.9 - 1.5	Very robust
Aluminium oxide	Excellent	Fair	~ 0.4	Fragile
Beryllia (beryllium oxide)	Excellent	Excellent	~ 0.25	Toxic
Silicon-Pads	Fair +	Excellent	~ 1.0 - 1.5	Convenient

Table 4.2 Thermal Resistances of Various Heatsink Materials

The thermal resistance of a heatsink is determined by:

- The size of the Heatsink;
- The number of fins;
- The total surface area - a ribbed fin design will be smaller than one using flat fins for the same thermal resistance;
- Thermal resistance within the aluminium itself - the actual alloy used, its thickness, etc;
- The colour - matt black is preferable;
- The orientation of the fins - vertical or horizontal (for the TE Collar vertical is best position);
- Air flow around the heatsink; and
- The heatsink temperature.

Surface	**Emissivity**
Polished aluminium	0.05
Polished copper	0.07
Rolled sheet steel	0.66
Oxidised copper	0.70
Black anodised aluminium	0.70 - 0.90
Black air-drying enamel	0.85 - 0.91
Dark varnish	0.89 - 0.93
Black oil paint	0.92 - 0.96

Table 4.3 The Emissivity of Various Surface Treatments

As a general rule, some heatsink designers calculate heatsink thermal resistance approximately equal to [11]:

$$\text{Thermal Resistance} = 50 / \sqrt{A} \qquad (4.3)$$

where A is the total surface area in cm^2

Air movement over the heat sink is required to minimise the temperature rise in the heat sink. With the use of natural convection, the thermal path from the base of the cold sink through the TEM and heat sink and ambient temperature must be carefully analysed. Therefore the use of heatsinks must be designed and positioned to ensure optimum power and heat transfer.

The radiation and convection load refers to the size of the TEM plate surface. As the heat increases, the output power increases and the plate surface increases. The heat dissipation at the hot side of the TE Collar is the sum of the heat load on the cold side (or sink) base plus the electrical output power from the thermoelectric module. The heat load dissipation at the hot side is essential to the output power, even with the small size of the heat load on the TEM cold side surface. This determines the amount of heat dissipated at the hot surface or via the heat sinks.

To increase the amount of output power, the TEMs are designed to ensure the maximum heat and cooling exposure to the TEM surface.

4.6.2 Types of Heatsinks

The types of heat sinks can be classified in terms of diverse production or manufacturing methods and their structural appearance or forms. The most common types of natural or forced air-cooled heat sinks are the following:

1. Stampings: Metal sheets of copper or aluminium are stamped into the desired form. This high volume manufacturing method is applicable for traditional air-cooling of electronic components and offers low cost applications to thermal problems. Because of advanced tooling, additional production options, such as taps, clips, and interface materials can be factory installed to reduce the broad manufacturing costs.

2. Extrusion: This is an inexpensive production method where fine structures can be shaped utilising this manufacturing procedure. Liquid aluminium is pressed through a pre-cast form to provide a long piece in the shape of the heatsink. After cooling, the heatsink 'piece' is cut into smaller bits according to size requirement. Utilising this method allows the formation of complicated figures and shapes capable of dissipating large heat loads. They may be cut, machined, and options added. Crosscutting produces omni-directional, rectangular pin fin heat sinks, and incorporating serrated fins with improved performance but with a slower extrusion rate. Limitations such as fin height-to-gap fin thickness, usually dictate the flexibility in design options.

3. Bonded/Fabricated Fins: In this manufacture method several smaller metal plates are bonded to the base plate, instead of one large folded plate. Most air-cooled heat sinks are convection limited, and the overall thermal performance depends on the surface area exposed to the air stream. Thermally conductive aluminium-filled epoxy is used to bond planar fins onto a grooved extrusion base plate, creating a high performance type heatsink. Due to the process, better fin height-to-gap aspect ratio is achieved which increases the cooling capacity without increasing volume requirements of the heatsink.

4. Castings: This method in the manufacture of heatsinks allows great versatility in the design and heatsink shapes. The drawback is that the fins produced via a die cast cannot be fine or delicate. This type of heatsink manufacturing technology is used for

high-density pin fin heat sinks providing the best performance when using assisted cooling

5. Folded Fins: With this type of heatsink manufacturing, thin corrugated or folded sheet metal in either aluminium or copper is bonded onto a base plate. This increases surface area and, consequently, the volumetric performance allowing better airflow of the heat sink. The heat sink is then attached directly to the heating surface. It is not suitable for high profile heat sinks due to the expense of production, availability and fin efficiency. However, this design offers light, compact and very high efficient heatsinks.

6. Cold forging and Milling: This production method is suitable for heatsinks with numerous small pin fins but manufacturing cost is high.

The performance of each individual and type heat sink varies and is determined according to the airflow through the heat sink fins. The volumetric heat transfer efficiency of each type can be defined as:

$$\eta = Q / m'c \, \Delta T_{sa} \qquad (4.4)$$

where:

Q Heat flow
m' mass flow rate through the heat sink
c Heat capacity of the fluid, T_{sa}
ΔT_{sa} Average temperature difference between the heat sink and the ambient air

The heat transfer efficiencies of each type heat sink configuration are listed in Table 4.3 below.

Heat sink type	**η as %**
Stamping & flat plates	10-18
Finned extrusions	15-22
Impingement flow, Fan heat sinks	25-32
Fully ducted extrusions	45-58
Ducted pin fin, Bonded & folded fins	78-90

Table 4.4 The heat transfer efficiencies of heat sink type [11]

Altitude (meters)	**Factor**
0, sea level	1.00
1000	0.95
1500	0.90
2000	0.86
3000	0.80
3500	0.75

Table 4.5 Altitude derating factors [11]

4.6.3 Effect of Heatsinks on Temperature Performance

The heat dissipated by the heatsink is absorbed by the ambient temperature and natural convection. To ensure optimal performance, the rise in temperature at the base must be kept at a maximum. The rise in the heat sink temperature above the ambient temperature is almost linear to the heat dissipated. Therefore the performance of the heatsink is determined from this linear ratio and is referred to as the thermal Heatsink resistance (HSR) in °C/Watt. A heat sink with a low thermal resistance will have a low temperature rise for a given heat dissipation. Therefore a heatsink with a low thermal resistance is preferable.

$$HSR = (T_{hs}-T_a) / (Q_h - IV) \qquad (4.5)$$

where:

HSR	Heatsink resistance
T_{hs}	Heatsink temperature
T_a	Ambient Temperature
Q_h	Hot side applied heat
I	Current delivered
V	Voltage delivered

The physical constrains also play a vital role on heatsink design and selection as the increase in size and fin spacing increases the heat dissipation with natural convection and lower the thermal resistance.

The heat sink used for the TE Collar, type 'Bond On' with 40-pin size is 19°C/Watt. The heat sink is black anodised to increase the heat dissipation to the ambient.

4.6.4 Effect of Heatsinks on Electricity Generation Performance

The TE Collar performance varies as the temperature of the heatsink change and therefore directly influence the electricity generated. As the temperature of the heatsink decreases, the power being generated decrease as the heat at the cold side (base) decreases.

To generate a constant voltage output, the temperature changes in relation to the heatsink must stay fixed. In order to control the current, a regulator needs to be inserted on the output leads from the TE Collar. The use of DC-DC Converter will ensure a constant current without any 'peaks'. If the heatsink temperature reduces, the DC-DC-Converter will ensure a constant current as a function to of the heatsink temperature.

4.7 Heat Transfer in Bonding Materials

Thermal adhesive was used to combine the TE modules and heatsinks to the aluminium band. The type used was a thermally conductive adhesive, suitable for bounding transistors to heatsinks and heatsinks to electronic boards.

The adhesive do not cover the complete heatsink or TEM, and therefore forms pockets. Heat gets 'trapped' in air pockets, which reduce transfer efficiency and rate. These air pockets form a barrier or resistance. Grease or other contaminants may also influence the surface contactability. The quantity of paint activator and adhesive applied also influence the bonding effect. The amount and spread of pressure applied directly affects a good bonding. The bonding was not controlled in an ideal environment, therefore, influenced the adhesive curing.

Item	Description	Adhesive	Activator
1.	Manufacture	RS Components Ltd.	RS Components Ltd
2.	Nature	Anaerobic adhesive	Solvent based activator
3.	Composition	Tetrahydrofurfuryl Methacrylate (1.00-20.00 Concentration) Cumene Hydroperoxide 95% (0.10-2.00 Concentration) Hydroxypropyl Methacrylate (1.00-10.00 Concentration)	Heptane (1.00-20.00 Concentration) Isopropanol (1.00-20.00 Concentration) Dihydropyridine (1.00-20.00 Concentration)
4.	Physical State	Paste	Liquid
5.	Colour	Blue	Yellow Amber
6.	Odour	Characteristic	Pungent
7.	PH Value	Not Determined	Not Determined
8.	Boiling Point	Not Determined	Approx. 80°C
9.	Flash Point	>100°C	<0°C
10.	Specific Gravity	1.6 – 1.7	0.8
11.	Solubility in Water	Immiscible	Immiscible
12.	Solubility in Acetone	Partially soluble	Miscible
13.	Vapour Pressure	Less than 1 at 20°C (mmHg@25°C)	Not Determined
14.	Toxicological	Skin, eyes and respiratory irritant Indigestion, Acute oral of: LD50 (rat)>5000mg/kg	Skin, eyes and respiratory irritant Indigestion, Acute oral of: LD50 (rat)>2000mg/kg

Table 4.6 Bonding material data and information as supplied by RS Components Ltd. [6].

The bonding material utilises two materials, an adhesive and an activator. See above, Table 3.1 for the chemical and physical properties as required by EC Directive 88/379/EEC and 91/155/EEC for handling and use of the product.

The TE modules manufacturer, TE Technology Inc, recommend torque limiting between 1023kPa to 2070kPa compression when applying bonding and connecting materials to the modules [10].

Due to the curve of the TE Collar, the bow of the surface reduces the thermal contact between the bonding of the TE modules and the heatsinks.

4.8 Power Supply and DC-DC Converters

4.8.1 Introduction to DC-DC Converters

In today's electronic applications, almost every piece of electronic equipment, e.g., computers and their peripherals, calculators, TV and hi-fi equipment, communication equipment and instruments, is powered from a DC power source. This power source is either a battery or a DC power supply converted or adapted from household AC line voltage. Most of this equipment requires not only DC voltage but voltage that is also well filtered and regulated. Since power supplies are so widely used in electronic equipment, these devices now comprise a substantial segment of the electronics market worldwide in an estimated excess of €5 billion annually. The TE Collar would be within this market as an addition or replacement to battery and DC powered equipment.

The following types of electronic power conversion devices in use today are classified as according to their input and output voltages:

1. DC to DC converter;
2. AC to DC power supply; and
3. DC to AC inverter.

Each of the three has its own area of application but this thesis will only focus on the first one, which are pertinent to the TE Collar. A power supply converting DC power must perform the following functions at high efficiency and at low cost to be considered effective:

1. Voltage transformation: Supply the correct DC voltage level(s).
2. Filtering: Smooth the ripple effect of the rectified voltage.
3. Regulation: Precise regulated and controlled output voltage level to a constant value irrespective of line, range of input voltages, load, and temperature changes.
4. Isolation: Separate electrically the output voltage from the input voltage source.
5. Protection: Prevent damaging voltage surges or spiking from reaching the output; provide back-up power or shut down during a 'brownout' scenario.

An ideal power supply (DC-DC Converter) would be defined by the supply of an even and constant output voltage regardless of variations in the voltage, load current, ambient or environmental conditions at 100% conversion efficiency and effectiveness.

4.8.2 DC-DC Converters Description, Performance and Operation Principles

In order to regulate and increase the voltage produced by the TE Collar, a DC-DC converter is required. DC-DC converters are commonly used to transform and distribute DC power in systems, applications and instruments. DC power is usually presented to a system in the form of a system power supply or battery. Generally with low-level voltages, isolation is not required. The DC-to-DC converter function is to regulate and step-up the voltage from low to high. It is used as a voltage limiter to ensure the voltage produced is prevented from rising above the point of damage to the electronics of the applications.

The DC-to-DC converter removes the need for a battery power source to help the TE Collar regulate voltage to applications. Therefore, its impact is on redundancy, dependency and costs. As the voltage output from the TE Collar varies and drops, the DC-to-DC converter keeps the supply output at a constant according to the equipment application requirements over a broad range of output voltage selections.

The LM2621 DC-DC Step-up converter, manufactured by National Semiconductor Corporation, were chosen due to the low start-up performance requirements typical generated by the TE Collar. See below, Table 3.2, for the parametric information:

The LM2621 is designed to provide a high efficiency, step-up DC-DC switching regulator for battery-powered, low input voltage systems and applications (which is targeted for in this thesis). It accepts an input voltage between 1.2V and 14V and converts it into a regulated output voltage. The output voltage can be adjusted between 1.24V and 14V. It has an internal 0.17Ω N-Channel MOSFET power switch built-in current limit, thermal limit, and voltage reference in a single 8-pin MSOP package. The manufacturer guarantee efficiencies up to 90% are achievable by using the LM2621 [7].

Item	Parametric Table of LM2621	
1.	Temperature Min (°C)	-40°C
2.	Temperature Max (deg C)	85°C
3.	Multiple Output Capability	No
4.	On/Off Pin	Yes
5.	Error Flag	No
6.	Input Min Voltage (Volt)	1.20
7.	Input Max Voltage (Volt)	14
8.	Output Current (mA)	2000
9.	Adjustable Output	Yes
10.	Output Range	1.24V-14V
11.	Switching Frequency (Hz)	2000000
12.	Adjusting Switch Frequency	Yes
13.	Sync Pin	No
14.	Efficiency (%)	90
15.	Flyback	Yes
16.	Inverting	No
17.	Step-Up	Yes
18.	Step-Down	No
19.	Regulator Type	Switching Regulator

Table 4.7 Parametric information of DC-DC Converter as supplied by National Semiconductor Corporation. [7].

The LM2621 starts from a low 1.1V input voltage and remains operational as low as 0.65V. On start-up, the control circuitry switches the N-channel MOSFET continuously at 70% duty cycle until the output voltage reaches 2.5V. After this output voltage is reached, the normal step-up regulator feedback and gated oscillator control scheme take over [9]. It was for this benefit the LM2621 DC-DC Step-up Converter was selected. The LM2621 is optimized for use in cellular phones and other applications requiring a small size, low profile, as well as low quiescent current for maximum battery life during stand-by and shutdown. A high-efficiency gated-oscillator topology offers an output of up to 1A. Additional features include a built-in peak switch current limit, and thermal protection circuitry [9].

The LM2621 is available in a Mini-SO-8 package. This package uses half the board area of a standard 8-pin SO and has a height of just 1.09mm (see Figure 4.4 below).

The high switching frequency (adjustable up to 2MHz) of the LM2621 allows for tiny surface mount inductors and capacitors (see Figure 4.5 and 4.6). Because of the unique constant-duty-cycle gated oscillator topology very high efficiencies are realized over a wide load range. The supply current is reduced to 80μA because of the BiCMOS process technology. In the shutdown mode, the supply current is less than 2.5μA [9].

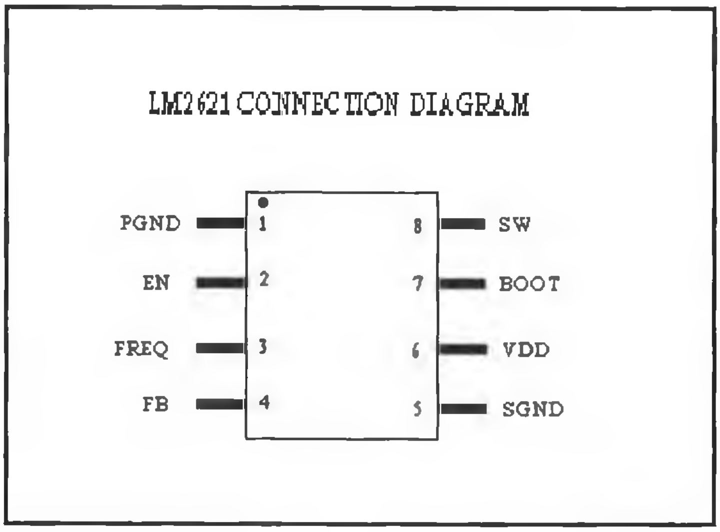


Figure 4.4 LM2621 Connection Details as supplied by National Semiconductor Corporation. [9].

4.8.3 DC-DC Converter Demo Board Operation Details

The LM2621 demo-board is set for 5.0V V_{OUT}. In this mode the LM2621 board can support up to 500mA of load current, provided V_{IN} is within the limits specified. By utilizing an schottky diode and an inductor rated for higher currents, load currents up to 1A can be realized, provided again that V_{IN} is within the limits specified. Schottky barrier diodes are commonly used due to; lower voltage drops, reduced recovery times, fast switching speeds and increased power conversion efficiency. The forward current rating of the diode should be higher than the load current, and the reverse voltage rating must be higher than the output voltage. However, the diode must withstand twice the reverse voltage that a diode sees in a full-wave bridge for the same input voltage.

The output voltage 'V_{OUT}' of the step-up regulator can be adjusted between 1.24V and 14V by connecting and changing the value of a feedback resistive divider made of RF_1 and RF_2. The resistor values are selected as follows:

$$RF_2 = RF_1 / [(V_{OUT}/ 1.24) - 1] \qquad (4.6)$$

where RF_1 is 150kΩ.

RF_2 can be selected using the above equation. A 39pF capacitor (CF_1) connected across RF_1 assist in feeding back most of the AC ripple at V_{OUT} to the FB pin (see Figure 4.4 & 4.5). This reduces the peak-to-peak output voltage ripple and improves the efficiency of the step-up regulator, because a set hysteresis of 30mV at the FB pin is used for the gated oscillator control scheme [9].

This type of control scheme enables the LM2621 to have an ultra-low quiescent current and provides a high efficiency over a wide load range. The switching frequency of the internal oscillator is proportional to the load current and programmable using an external resistor and can be set between 300 kHz and 2 MHz.

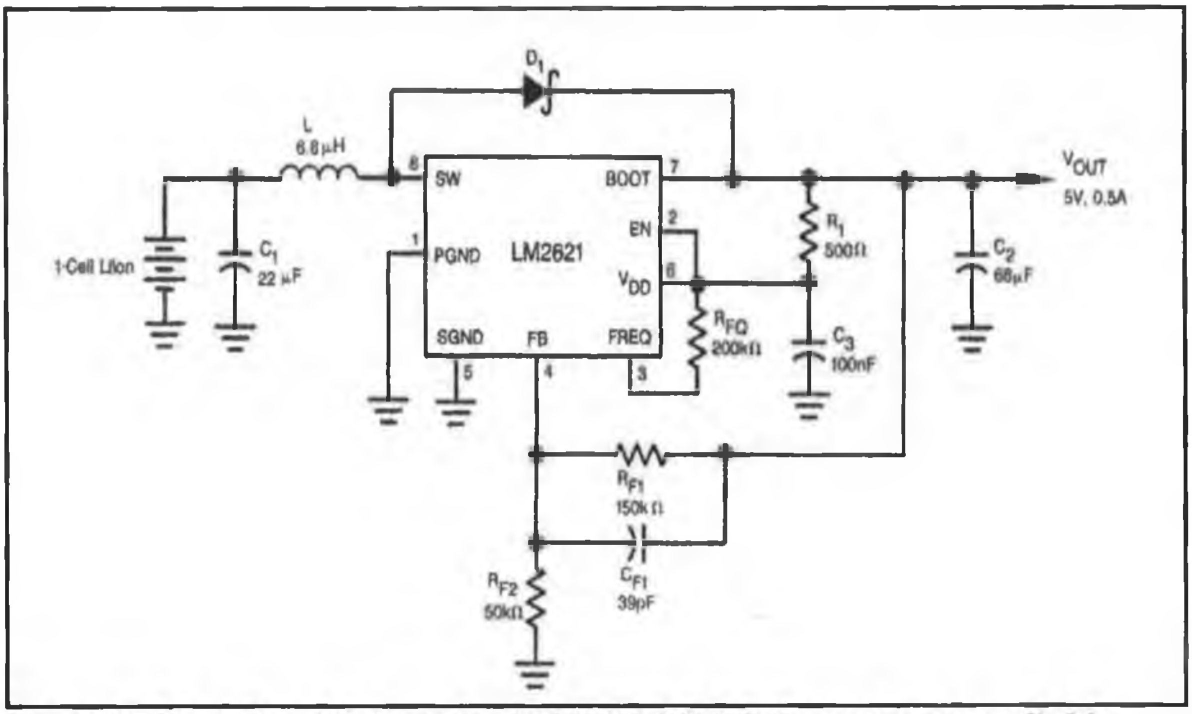


Figure 4.5 Demo Board Schematic of LM2621 DC-DC Converter as supplied by National Semiconductor Corporation. [7].

The gated oscillator control scheme uses a hysteresis window to regulate the output voltage ripple. When the output voltage is below the upper threshold of the window, the LM2621 switches continuously with a fixed duty cycle of 70% at the switching frequency selected. In the first part of each switching cycle, the internal N-channel MOSFET switch is turned on. This causes the current to ramp up in the inductor (L_1) and store energy. During the second part of each switching cycle, the MOSFET is turned off. The voltage across the inductor (L_1) reverses and forces current through the diode (D_1) to the output filter capacitor (C_{F1}) and the load. Thus when the LM2621 switches continuously, the output voltage starts to ramp up. When the output voltage hits the upper threshold of the window, the LM2621 stops switching completely. This causes the output voltage to drop because the load depletes the energy stored in the output capacitor (C_2). When the output voltage hits the lower threshold of the hysteresis window, the LM2621 starts switching continuously again, causing the output voltage to ramp up towards the upper threshold. [9]

The maximum acceptable voltage at the BOOT pin (Pin 7) is 10V. With bootstrapped operation, the V_{OUT} voltage supplies the V_{DD} pin of the capacitor C_1 (see Figure 4.5). The V_{DD} pin is rated between 2.5V and 5.0V. When the output voltage V_{OUT} is between 2.5V and 5.0V a bootstrapped operation is achieved by connecting the V_{DD} pin (Pin 6) to V_{OUT}. However, if the V_{OUT} is outside this voltage range a non-bootstrapped operation occurs and the V_{DD} pin is connected to a voltage source whose range is between 2.5V and 5V. This can be either the input voltage V_{IN}, V_{OUT} stepped down using a linear regulator, or a different voltage source available in the system.

If neither V_{OUT} nor V_{IN} are in the 2.5-5.0V range, a voltage in this range needs to be generated from either V_{IN} or V_{OUT} using a zener diode. Resistor R_1 should then be connected between this voltage and V_{DD} (Pin 6) of LM2621.

An internal cycle-by-cycle current limit serves as a protection feature. This is set between 2.85A to 4A, in order not to affect the normal operating conditions. An internal thermal protection circuitry disables the MOSFET power switch when the junction temperature reaches about 160°C and re-enabled when the temperature drops below 135°C.

The LM2621 incorporates a shutdown mode that reduces the quiescent current to less than a guaranteed 2.5μA over the temperature. The control of the shutdown mode is via the active-low logic input EN (Pin 2). During shutdown, all feedback and control circuitry is turned off and the regulator's output voltage drops to below the input voltage. When the logic input to this pin falls below $0.15V_{DD}$, the device goes into shutdown mode. The logic input to this pin should be above $0.7V_{DD}$ to function in normal step-up mode.

The switching frequency of the oscillator is selected with an external resistor (R_{FQ}) connected between FREQ and V_{DD} pins. A high switching frequency enables the use of small surface mount inductors and capacitors and results in a very reduced solution size. The shielded inductor (6.8μH) has a saturation current rating higher than the peak circuit operation current. The inductor is connected to the SW pin as close to the IC. This is to minimize radiated noise, flux linkage with circuit components and interference from the normal operation of the circuit.

The circuit uses Tantalum chip capacitors for the input (22μF) and output (68μF) filter capacitors (see Table 4.3). The capacitors have a higher DC working voltage rating than the maximum input voltage.

4.8.4 The advantages of DC-DC Converters

The advantages to use DC-DC- converters in the TE Collar electrical connections are as follows:

1. Power where you need it, rather than routed in.
2. Non-isolated prevents grounding problems.
3. Isolation allows the floating of a power supply.
4. Extra wide input voltage range, or multiple inputs.
5. Lower cost in high volume.
6. Higher efficiency can be achieved.
7. Extra protection from line voltage fluctuations, noise, and spikes.
8. Several voltages, or several isolated voltages can be produced.
9. Using a single converter for multiple voltages cuts the DC-DC converter overhead losses.
10. Adjustable voltage DC-DC converter speeds product design.
11. Special voltages gives freedom from having to work around off-the-shelf solutions.
12. Output sequencing can be incorporated into the DC-DC converter.
13. Current limited converters are perfect for battery charging, and laser capacitor banks.
14. Remote voltage sensing allows the DC-DC converter to control the voltage at the end of a cable.
15. Low noise, special size or mechanical configuration, extra wide voltage range. Noise reduction can be tailored to your needs. DC-DC converter switching frequency can be selected to avoid sensitive bands.

16. Annunciation allows you to monitor the state of the DC-DC converter.
17. Off-the-shelf DC-DC converters sometimes require to run the output close to the voltage input limit, which is hard on the DC-DC converter, reduces the power efficiency, thus increasing the noise and temperature.
18. The DC-DC converter can be configured to have a battery backup.
19. Custom features available in custom and semi-custom DC-DC converters are:
    19.1. Nominal Input Voltage;
    19.2. Input voltage range;
    19.3. Cut off if voltage goes outside a certain range;
    19.4. Wide range of output voltage;
    19.5. Output voltage stability; and
    19.6. Output current limit;
20. Ability to adjust voltages in the factory or in the field.
21. Ability to adjust voltage in the factory, or as a feature of the end use via a potentiometer.
22. Ability to control the voltage with an external signal, for example in a light dimming circuit, capacitive discharge spot welder, or laser capacitor bank.
23. Size and mechanical configuration.
24. Simultaneous Buck and Boost converter. Buck converters can only reduce the input voltage; Boost converters can only increase the input voltage.
25. For multiple outputs, low current outputs can be implemented with a linear circuit, which is cheaper than a separate DC-DC converter and reduces noise.

4.8.5 Electrical Connections and Mechanical Mountings

The LM2621 Demo Board circuit ships fully assembled and tested, the circuit needs no adjustment. The LM2621 Demo Board connects directly to the application as shown in the schematic (Figure 4.5) above. The terminals are directly connected with Banana Jacks into the electrical system.

4.8.6 DC-DC Converter Circuit Description

The LM2621 Demo Board electronic module is a Step-Up DC-DC Converter. This Step-Up is accomplished with an integrated Mini-SO-8 circuit. The IC high switching frequencies and high peak currents require a proper layout and design of the PC board. The components such as the inductor, input and output filter capacitors, and output diode are placed close to the regulator IC. To reduce EMI and ground-bounce, which can cause malfunction and loss of regulation by corrupting voltage feedback signal and injecting noise into the control section, the voltage feedback network (RF_1, RF_2, and CF_1) is situated close to the FB pin. Noisy traces from the SW pin are positioned away from the FB and V_{DD} pins. Adequate copper area is provided to dissipate the heat due to power loss in the circuitry and prevent the thermal protection circuitry in the IC (LM2621) from shutting the IC down.

Summarise of LM2621 Features:

- Small Mini-SO8 Package;
- 1.09 mm Package Height;
- Up to 2 MHz Switching Frequency;
- 1.2V to 14V Input Voltage;
- 1.24V - 14V Adjustable Output Voltage;
- Up to 1A Load Current;
- 0.17 Ohm Internal MOSFET;

- Up to 90% Regulator Efficiency;
- 80μA Typical Operating Current; and
- <2.5μA Guaranteed Supply Current In Shutdown.

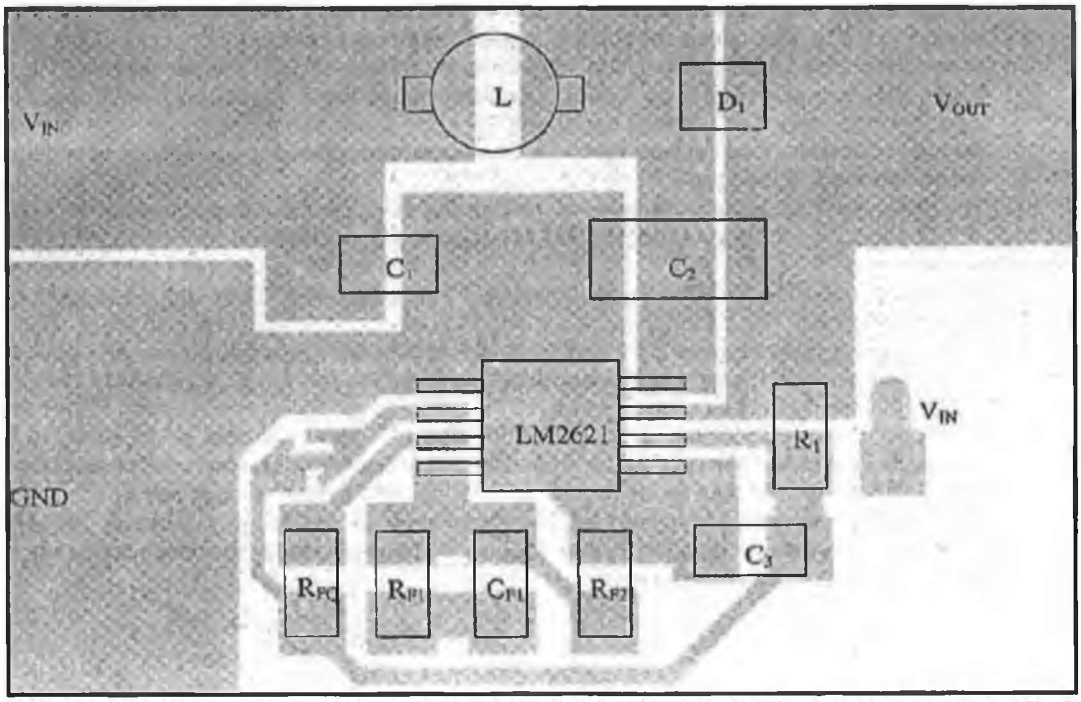


Figure 4.6 Demo Board Layout of LM2621 DC-DC Converter as supplied by National Semiconductor Corporation. [7].

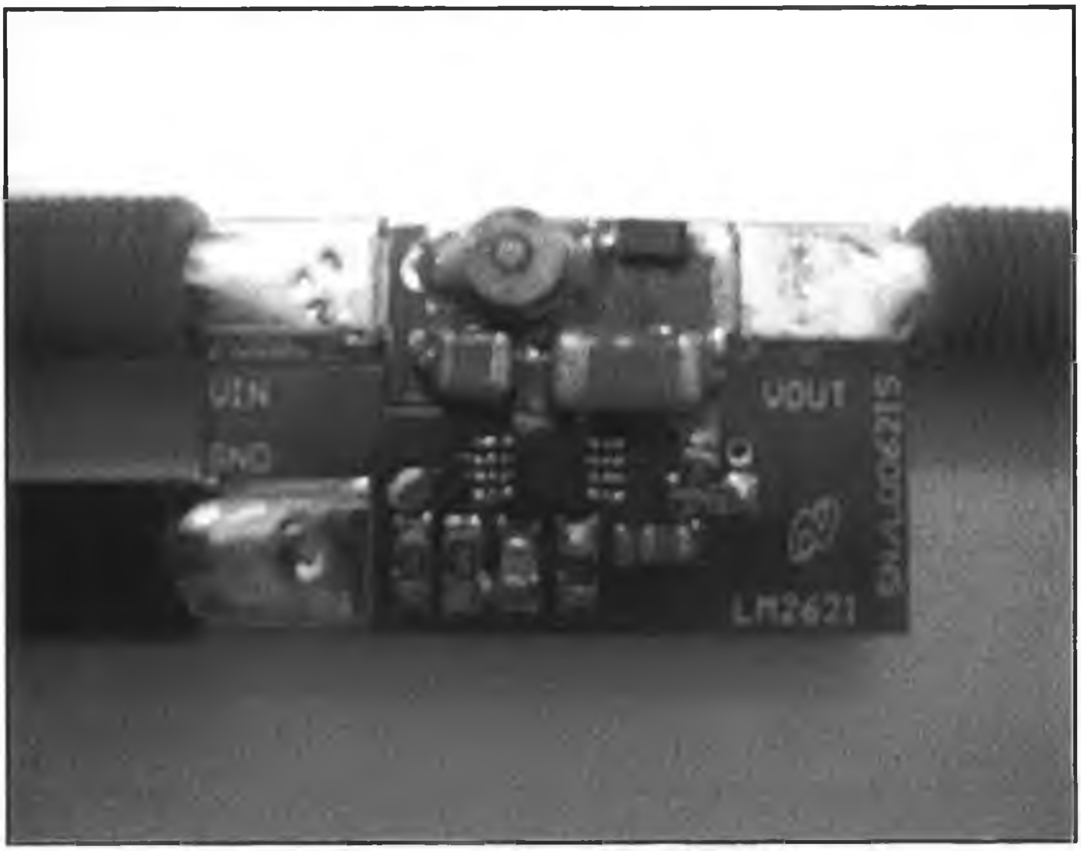


Figure 4.7 Board Component Layout of LM2621 DC-DC Converter as supplied by National Semiconductor Corporation. [7].

Bill-of-Materials For LM2621 Demo-Board			
Component	**Value**	**Part Number**	**Manufacturer**
L	6.8uH	DT1608C-682	Coilcraft
Dl	Schottky	MBR0520LT3	Motorola
Cl	22uF, 6.3V Tantalum	595D226X06R3B2T	Vishay-Sprague
C2	68uF, 10V Tantalum	595D686X0010C2T	Vishay-Sprague
U1	IC	LM2621	National Semi
RF1	150kΩ, 1/4W	0805 Body Size	Any Manufacturer
CF1	39pF, Ceramic 16V or Higher		
RF2	50kΩ, 1/4W	0805 Body Size	Any Manufacturer
C3	0.1μF, Ceramic 16V		
R1	500kΩ, 1/4W	0805 Body Size	Any Manufacturer
RFQ	200kΩ, 1/4W	0805 Body Size	Any Manufacturer
V_{IN}	Banana Jack	861-R	SPC Technology
V_{OUT}	Banana Jack	861-B	SPC Technology
V_{GND}	Banana Jack	861-GR	SPC Technology

Table 4.8 Bill of Materials information of LM2621 Demo Board Converter as supplied by National Semiconductor Corporation. [7].

4.8.7 Applications for the TE Collar and DC-DC Converter

- 2-Cell and 3-Cell Battery-Operated or powered Equipment;
- PCMCIA Cards, Memory Cards;
- Flash Memory Programming;
- TFT/LCD Applications;
- 3.3V to 5.0V Conversion;
- GPS Devices;
- Two-Way Pagers;
- Palmtop Computers;
- Power source for Cameras;
- Hand-Held Instruments;
- Hand-Held communication equipment;
- PDA's, Cellular Phones;
- Power source for camcorders;
- Power source for applications and appliances which require higher cell voltage than batteries can provide; and
- Failsafe power source to rescue equipment.

See Chapter 7, Table 7.3 for the comparison of Hand Held devices electrical power.

4.9 Conclusions

In order for the TE Collar to produce a high output voltage and current, the use of optimal size heatsinks to the system is required. Consideration must therefore be given to the practicality of the overall system aspects and the initial design.

The low thermal efficiencies of TE devices make them acceptable for use in remote locations or in unusual situations. These include for power generation where conventional sources are unavailable or not replaceable. They constitute long-life power sources in which the human body provides the energy or other heat sources. In addition of no moving parts, it does not affect the application, require replacement or maintenance.

The materials and construction of the TE Collar play a vital part in ensuring the best application and efficiency under the specific conditions. With new materials available, the construction method, layout, size and even positioning of the TE Collar will change. Since this research focuses on materials already available on the market, the expected performance and feasibility from these materials must be highlighted. With the materials available in the market, it is possible to construct a working and perhaps a commercial available device to generate electricity as proposed in this thesis.

Chapter 5- Body Heat Flow and Generation Considerations

5.1 Introduction

It is important to understand the heat source, or thermal load (the human body) in MPTG. The human body generates energy in the form of heat, electricity, magnetism and wave energy. In a healthy younger person, the body temperature fluctuates within 36.2˚C to 37.2˚C. However, this temperature does not remain constant throughout the day and the internal of core body temperatures may vary as much as 0.5˚C to 1˚C although in a set range. The body temperature tends to be lowest in the morning hours, from 2 am to 4 am, while the body is resting or asleep. The body tends to be warmer in late afternoons; from 4 pm to 6 pm or after exercise or activities. It has been noted that this variation is present even in people working night shifts. The explanation is the body's internal mechanisms or 'clock' is very resistant to change.

According to James Winshall, M.D., "Different warm-blooded species have different set points, but all fall within a relatively narrow range [1]". Humans are warm-blooded and adjust or regulate temperature to stay within a certain set range regardless of surrounding thermal changes. This is due to the hypothalamus, which cause body temperature to be regulated. The hypothalamus is situated in the region of the brain that serves as the body's thermostat. The hypothalamus adjusts body's temperature, balancing heat gain against heat loss through several physical and behaviour mechanisms [1]. The body will therefore exert more energy to keep the body at a set temperature. While the core temperature is carefully modulated, the temperature of the skin is unregulated and varies from about 31˚C to 35˚C in normal activities and environment.

For this research, the skin temperature and the associated physiologic control system, behaviour effects and environment conditions influencing and regulating the core and skin temperature are of vital importance.

5.2 Normal Body Temperature

To establish accuracy in heat flow measurements, a reference point is required to calculate the heat flow transfer to and from the TE Collar. Since the ambient temperature is constantly changing, the reference point utilised must be a constant and reliable. The body core is considered the reference point of all calculations in this thesis.

The problem is that scientist cannot agree to what this 'reference point' or the normal body core temperature. "the mean normal body temperature of 98.6 degrees F (37˚C). What is surprising is that recent medical research has posited that the mean normal temperature is really 98.2 degrees F (36.8˚C)!"[2]

Major effects on body temperature discrepancies are the following:

1. Consumption of hot or cold drinks, improper thermometer placement, saliva and swallowing and breathing can affect oral temperature measurement results.
2. Temperatures measured under the armpit (axilla) are less accurate. The core body temperature is best assessed by measurements in the rectum or the ear drum (tympanic membrane).
3. Temperatures measured in the rectum are usually 1 degree higher than oral temperatures, and axillary temperatures are 1 degree lower.

4. Measuring extremities, such as the hands and feet, have the lowest temperature because they are removed from the body core (the heart and brain), where most of the body heat is concentrated.
5. The ambient temperature effects on fresh urinal may cause considerable temperature fluctuations in a short time.

Table adjusted from: The Physics Factbook: Edited by Glenn Elert [4]

<table>
<tr><th>Bibliographic Entry</th><th>Result
(with surrounding text)</th><th>Standardized Result</th></tr>
<tr><td>Campbell, Neil A. Biology. 3rd ed. California: Benjamin Cummings, 1987: 790.</td><td>"... a human can maintain its 'internal pond' at a constant temperature of 37 °C"</td><td>37 °C</td></tr>
<tr><td>"Temperature, Body." World Book Encyclopaedia. Chicago: Field Enterprises, 1996.</td><td>"... a healthy, resting adult human being is 98.6 °F (37.0 °C)"</td><td>37.0 °C</td></tr>
<tr><td>Simmers, Louise. Diversified Health Occupations. 2nd ed. Canada: Delmar, 1988: 150-151.</td><td>"... the normal range for body temperature is 97 to 100 degrees Fahrenheit or 36.1 to 37.8 degrees celsius"</td><td>36.1 - 37.8 °C</td></tr>
<tr><td>Eisman, Louis. Biology and Human Progress. Englewood Cliffs, NJ: Prentice Hall, 1972: 125.</td><td>"... fairly constant temperature of 98.6 degrees "</td><td>37.0 °C</td></tr>
<tr><td>McGovern, Celeste. "Snatched From an Icy Death." Alberta Report/Western Report. Academic Abstracts: United Western Communications, 1994: 2.</td><td>"... core body temperature... the normal 37 °C"</td><td>37.0 °C</td></tr>
<tr><td>Vital Signs. Family Internet. Applied Medical Informatics, 1996.</td><td><table>
<tr><th>Age</th><th>Temperature (°F)</th></tr>
<tr><td>0 - 3 month</td><td>99.4</td></tr>
<tr><td>3 - 6 month</td><td>99.5</td></tr>
<tr><td>6 month - 1 year</td><td>99.7</td></tr>
<tr><td>1 - 3 year</td><td>99.0</td></tr>
<tr><td>3 - 5 year</td><td>98.6</td></tr>
<tr><td>5 - 9 year</td><td>98.3</td></tr>
<tr><td>9 - 13 year</td><td>98.0</td></tr>
<tr><td>> 13 year</td><td>97.8 - 99.1</td></tr>
</table></td><td>36.6 - 37.3 °C</td></tr>
</table>

Table 5.1 Temperature of a Healthy Human (Body Temperature)

This research paper presumes that the body core temperature of a normal healthy human at rest would be at the reference of 37.0°C measured orally. The human body attempts to keep its internal temperature constant via body temperature regulation. Human life is only compatible with a narrow range of temperatures as listed below in Table 5.2 and Figure 5.1:

Temperature (°C)	Symptoms
28	muscle failure
30	loss of body temp. control
33	loss of consciousness
37	normal
42	central nervous system breakdown
44	death*

(*by irreversible protein "denaturation", or unfolding; once the protein shape changes, they cease to function properly.)

Table 5.2 Human body core temperature variations and effects

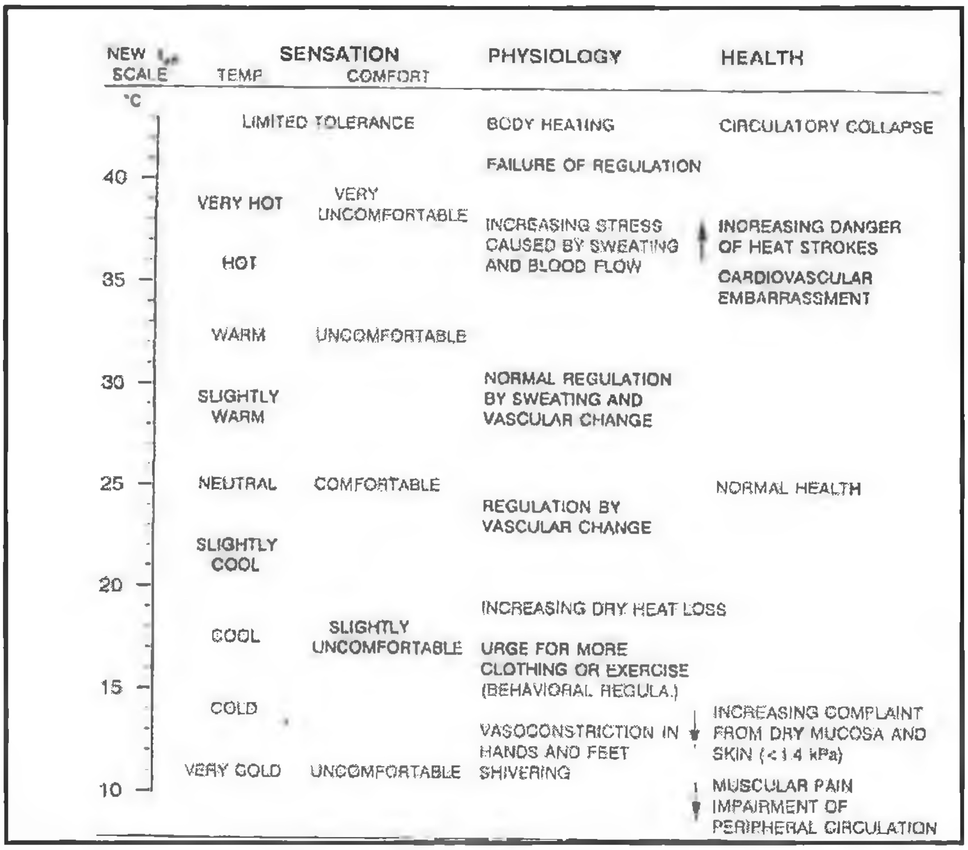


Figure 5.1 Related Human Sensory, Physiological, and Health Responses for Prolonged Exposure- ASHRAE [7]

5.3 Body Heat Flow

The body is constantly generating heat and must take active steps to lose that heat. The use of this energy focuses on utilising TE modules placed around the neck near the main arteries to the brain which generates the highest output of heat conductance near the skin and would be the most efficient positioning for such devices other than the head. The Table 5.3 illustrates the power cost of various common activities [6]:

Activity	Energy Cost (Cal/m^2hr)	Energy Cost (J/m^2hr)
sleeping	35	146
sitting	50	209
working at a desk	60	251
standing	85	356
washing & dressing	100	418
walking (5 km/h)	140	586
light work	160	670
bicycling	250	1046
medium work	265	1110
swimming	350	1465
heavy work	440	1842
running	600	2512

Table 5.3 Activities with associated Energy Cost

Approximately 80% of these energy costs are waste heat. The consideration is cold weather and the energy the body uses to stay warm. The mechanisms used or affects the heat transfer function of the body are conduction, convection, radiation and evaporation.

5.3.1 Conduction:

Conduction is the transfer of heat between two substances or objects in contact with each other. The following equation for the rate of heat flow 'ΔQ' in Watts apply:

$$\Delta Q / \Delta t = kA \, \Delta T / \Delta x, \qquad (5.1)$$

where 'k' is the thermal conductivity, 'Δt' the given time difference in seconds 'A' is the body area, 'Δx' the material thickness and 'ΔT' the temperature difference in Kelvin.

Some useful conductivity figures are given in the following table below:

Substance	**Conductivity**
Air (0°C)	0.0243 W/m.K
H_2O (20°C)	0.6 W/m.K
Cu	390 W/m.K
Tissue	18 kcal.cm / m^2hr.K

Table 5.4 Materials/ Substances with their Conductivity

Materials with high thermal conductivities are good conductors of heat whereas materials with low thermal conductivities are good insulators.

5.3.2 Convection:

Convection is the transfer of heat between a moving fluid or gas (wind or water) and object surface or due to differences in density in the fluid. The convection rate of heat flow 'ΔQ' in Watts is:

$$\Delta Q / \Delta t = 14.5\ A\ v\ \Delta T \qquad (5.2)$$

where 'A' is measured in square meters and 'v' is the (wind) speed in meters/ second. Still air actually has a convection velocity of 0.23m/s (called "natural convection") because warm air rises. For the body in air, convection is in series with private climate conduction. Within the body, blood convection is used to move the heat from the inside of the body to the skin. Here the area is the surface area of the capillary bed, which for the average adult male is about $160m^2$. Using the skin temperature and heat current above, blood flow must be around 2mm/s, which is the correct order of magnitude. Since the specific heat of blood is larger than that of air, it is expected that the thermal current to be larger for blood, and hence the velocity to be smaller than this estimate.

5.3.3 Radiation:

Radiation is the transfer of heat from a warmer object to a cooler object without physical contact. Thermal Radiation is the emission of electromagnetic waves (the body emit in the infrared wavelengths) due to the agitation of the molecules of the body. The body can absorbed, reflect and transmit radiation. The radiation current (in Watts) is as follows

$$\Delta Q / \Delta t = \varepsilon\ \sigma\ A\ (T_b{}^4 - T_a{}^4) \qquad (5.3)$$

where 'ε 'is the "emissivity", which is 0.97 for human skin independent on colour, 'σ'is the "Stefan-Boltzmann's" constant ($5.67 * 10^{-6}$ W / m^2 $(K)^4$) and 'T' the temperature in Kelvin, ('b' denotes body, while 'a' denotes ambient temperature). For the above equation, the body's radiation power output is only about 0.002 W.

When considering radiation absorbed by the skin from the sun, the emissivity (which is equal to the absorptivity) depends on frequency and therefore on skin colour (it is known that this is not an equilibrium situation, because many people can get severe sun burns). Using data on the reflectivity of human skin as a function of wavelength (where reflectance is $1 - \varepsilon$), a weighted average emissivity for various skin colours can be constructed (weighted by the solar power output as a function of wavelength). Using this data, Caucasian skin has a weighted average 'ε'of 0.566, while Negroid skin has a weighted average 'ε 'of 0.838.

5.3.4 Evaporation:

Evaporation is simply the change of phase of sweat. The rate of sweat is then related to the thermal current by the latent heat of vaporization:

$$\Delta Q / \Delta t = (\Delta m / \Delta t)\ L. \qquad (5.4)$$

At body temperature, the latent heat of vaporization of water is 580 cal/g (2428.46 J/kg). Up to 4L/hr sweat is possible and for longer periods (possibly up to 6 hours), 1 L/hr is common.

The body loses water vapour via respiration. With each breath of air (about 6L for a normal person), the air is humidified to saturation in order to be used efficiently by the body. When air is exhaled, vapour forms part of its make-up. This results in evaporative loss, which at high altitudes can equal sweat as a cooling factor. It is due to this reason that evaporation a major contributor to heat regulation. The body's functions are severely restricted when 10% of body weight is lost due to dehydration.

In relation to cold weather and the effects on the body, the body has a number of mechanisms to help cope with these changes. The surface capillaries constrict when the ambient temperature is above 19°C (for a nude person). Shivering raises the average human body metabolic rate to about 250kcal/m^2 hr (relative to body surface area). For a well-insulated body, evaporative losses in breathing however, limit the ability to withstand cold temperatures. The various modes of heat transfer can be summarized with the following diagram (Figure 5.2) below:

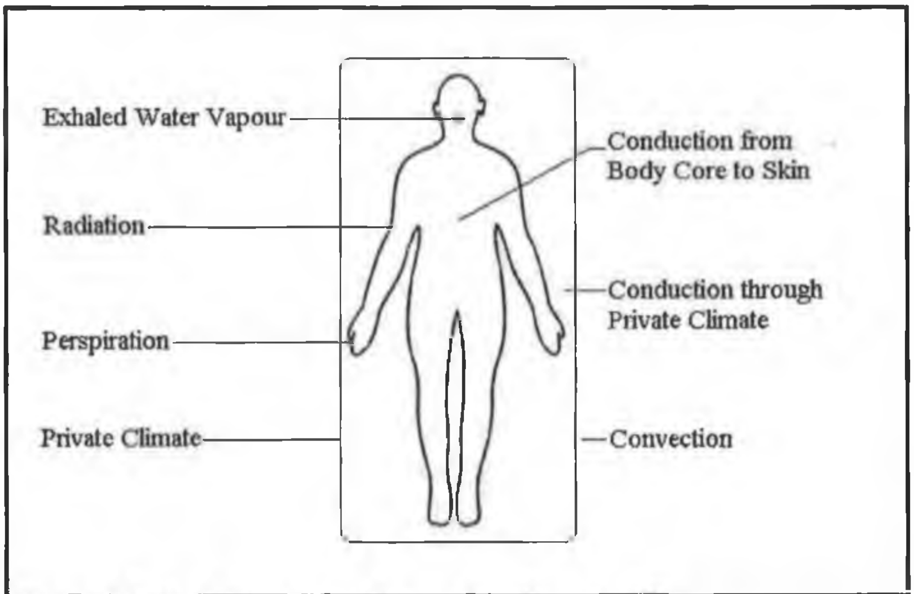


Figure 5.2 Body heat transfer modes diagram [5].

5.4 The Body Cellular Metabolism

The term "basal metabolism" refers collectively to those physiological functions that the body performs while resting. The basal metabolic "rate" is the power required to sustain those functions. Many of these functions are macroscopic, such as the heart beating, respiration and digestion. Two thirds of basal metabolism is required to move ions against concentration gradients and one third to power the sodium pumps [9]. The metabolic rate may be taken as:

$$h = 3.2m^{0.75} \qquad (5.5)$$

where 'h' is taken the basal metabolic rate in Watt and 'm' is the mass of the body in kilogram [8].

Cellular metabolism as a quantity must be broken down to several different energies. This is required due to the number of chemical reactions present in the body. The internal energy 'U' denotes thermal energy and work done (W = P.V at constant pressure) by or against the outside environment. Between the free energy available to create chemical reactions and entropic energy (which is the consequence of the degeneracy of the system) must be differentiated between. The latter contributes to the random nature of the system. Total enthalpy 'H' is defined:

$$H = U + P V \tag{5.6}$$

where 'U' is the internal energy, 'P' is the pressure, and 'V' is the volume as well as:

$$H = G + T S. \tag{5.7}$$

Where 'S' is the entropy and 'G' the irradiation or free energy in Watt. The Gibbs Free Energy is defined as a thermodynamic quantity that takes into account both enthalpy and entropy: G = H - TS where 'H' is enthalpy, 'S' is entropy, and 'T' is absolute temperature [12]. The change in free energy 'ΔG' for a process takes into account the changes in enthalpy and entropy and indicates whether that process will be thermodynamically favoured at a given temperature. The changes in energy can be written as:

$$\Delta H = \Delta U + PV \tag{5.8}$$
$$= \Delta G + T\Delta S \tag{5.9}$$

the reactions under examination takes place at constant pressure (isobaric) and constant temperature (isothermal). Physicists and chemists view this use of entropy differently. For the chemist, equation 5.9 means:

$$H_P - H_R = G_P - G_R + T\,(S_P - S_R) \tag{5.10}$$

where '$_P$' and '$_R$' denote products and reactants. Enthalpy is considered as the 'heat of formation' and free stored energy where entropy of that is of a single molecule.

Considering entropy as the energy 'wasted' to thermal excitations in the cell. This energy is that which the body wastes as discussed. The body is regard as a closed system and the enthalpy conserved, therefore:

$$\Delta S = |\, G_P - G_R \,| \,/\, T, \tag{5.11}$$

or,

$$\Delta S = |\, G_{in} - G_{\text{stored for later use}} \,| \,/\, T. \tag{5.12}$$

The metabolic processes involve chemical reactions that in turn release energy ("exergonic" reactions). The reactions require energy to in order to occur ("endergonic" reactions) [9]. The former supply the needs of the latter. As indicated by equation 5.12, part of the energy released by an exergonic reaction is free to be used by an endergonic one. There is always 'waste' entropic energy. The efficiency of the system is calculated as the ratio of the work done by the system to the energy it requires to accomplish that work:

$$\eta = W\ \text{done} \,/\, E\ \text{input}, \tag{5.13}$$

which is dimensionless. This is equivalent to, for our purposes,

$$\varepsilon = G_{\text{stored for later use}} / G_{in} \quad (5.14)$$

These system-wide physiological efficiencies are in the region of about 20 %. Equilibrium conditions must therefore exist when the free energy G is at a minimum or mathematically, when

$$\Delta G = 0. \quad (5.15)$$

This situation however corresponds to death, since no free energy is available to drive endergonic reactions. **Life requires a steady state relatively far from equilibrium, and in all cases that we know of, this state is maintained by sustaining non-equilibrium concentration gradients across membranes** [9]**.** This activity requires a constant influx of energy, and the consequent generation of entropy.

If ΔG is...	**The process is...**
Negative $\Delta G < 0$	Thermodynamically favoured
Zero $\Delta G = 0$	Reversible; at equilibrium
Positive $\Delta G > 0$	Thermodynamically unfavoured, the reverse process is favoured

The features of metabolic reactions are summarised as follows:
1. All reactions must proceed spontaneously, either because they are exergonic or because they are coupled with a sufficiently exergonic reaction to provide the extra energy necessary to drive an otherwise non-spontaneous endergonic reaction [9].
2. The free energy and entropy changes are independent of path. Changes in their values for a whole process are the sums of the changes for individual reactions.
3. The use of small steps between equilibrium states allows the biological system to approach 'reversibility', which increases efficiency.
4. Efficiencies of 'cyclic' processes (the final state is the same as the initial one or end at the beginning) are generally better than non-cyclic ones.
5. The energy selected where $U = 0$ is subjective.

5.5 Heat and Body Temperature Considerations

Heat (Q) is thermal energy of particles randomly colliding with each other and objects in their environment. It has dimensions of energy, but it is NOT a state variable: unlike temperature, its value does depend on the history of the system. For instance, adding heat can isothermally expand a system, or its pressure can be slowly decreased without the addition of heat. Yet, the final pressure, temperature and volume are the same.

The heat energy of a system can be written as the product of two state variables, temperature and entropy. Entropy is a measure of the "degeneracy" or "degeneration" of a system (the number of states which all have the same energy, and are therefore all equally accessible) or the disorder of a system:

$$S = \sigma_B \ln (W) \quad (5.16)$$

where 'S' is Entropy, 'σ_B' is the Boltzmann's constant and W is the number of thermodynamic sub states of equal energy or degeneracy.

Entropy is an intrinsic state variable. In a completely isolated system, it can never decrease. Since high degeneracy is associated with randomness, it is often said that entropy is a measure of the "disorder" of a system. Disorder however is too imprecise for physics.

Heat is most often measured in 'calories' (cal). One calorie is 4.186 J; it is the amount of heat needed to raise one gram of water 1K. The temperature of a substance changes as heat energy is added to it. The 'heat capacity' (C) of an object is the ratio of change in heat to change in temperature, and the 'specific heat' (c) of a substance is the heat capacity per unit mass. We therefore have

$$\Delta Q = m\,c\,\Delta T \qquad (5.17)$$

The specific heat of water is 1cal/gK by definition. The specific heat of human tissue is 0.85. That of air is 0.23.

For a given substance at a given pressure, phase changes occur at well-defined temperatures. For a given substance, the heat change per unit mass required for a phase transition is called the 'latent heat' h in kJ/Kg. This means that

$$\Delta Q = m\,h. \qquad (5.18)$$

The neat heat transfer from the body can be written as:

$$Q = (U - G)\,A \qquad (5.19)$$

where 'U' is the energy leaving the body or heat rejected, 'G' the energy incident on the body and 'A' the area of the body.

For further considerations on biochemistry and body cell metabolism, see Addendum, Chapter 11, Item 11.3

5.6 Normal body temperatures, the neutral zone, the body temperature set point, and the inverse relationship between core and skin temperature

The skin is the largest organ of the body in surface and in weight. An adult skin covers approximate $2m^2$ and weights about 4.5-5kg or 16% of the total body weight. The average thickness of the skin is 1-2mm and ranges from 0.5mm at the eyelids to 4mm at the heels [13].

The neutral zone for humans are defined as the range of skin temperatures over which adjustments of skin blood flow sufficiently to maintain core temperature constant in a resting person. This range of the skin temperature varies according to each individual but is approximate from 33°C to 35°C. This range would be considered as normal body temperature.

It is the understanding that changes in normal body temperature must occur under the control of the regulatory system that operates in the neutral zone and possibly a set point in the body thermoregulation; therefore this must be manifest in the control of skin blood flow. In a normal resting metabolism, the changes in core temperature must be the consequence of the changes in skin blood flow. The control system of skin blood flow in the neutral is still unclear. However, in scientific discussions, thermoregulation is described in terms of a 'set point' and this notion may or may not imply a specific concept of how the control system works.

When considering a slight change of 2˚C in skin temperature, it may seems like a minor thermal stress, but without the regulatory response the core temperature would ultimately change as much as skin temperature. Yet, the body core temperature would rise only slightly. Therefore the crude estimate of the overall change in skin blood flow that accomplishes the adjustment of heat transfer in response to skin temperature changes

5.7 Influences and Conditions Affecting Body Temperature

The body responds when core temperature falls to retain heat and conserve energy. The responses are vasoconstriction, the release of epinephrine, non-pinephrine, thyroid hormones and shivering. In the same manner when the core temperature increases, the heat loss responses include vasodilation, decreased metabolic rate and evaporation of perspiration [13].

Below some influences and conditions that affect the body temperature regulation and the production of heat or energy are listed.

5.7.1 Extreme activity:

The hypothalamus compensates for the increase in heat that the body generates during exercise. The body 'cool down' period may continue after strenuous exercise. Under strenuous exercise, the body may experience normal temperatures of up to 38.9˚C or more. During less prolonged or less strenuous exercise, the temperature gradient is much less and will return to normal body temperature within a short time.

5.7.2 Ovulation:

A women's body temperature is lower during the two weeks before ovulation, the stage of the menstrual cycle when an egg is released from the ovary. At the time of ovulation, there is an increase of 1˚C, when there is a surge in the secretion of progesterone, one of the hormones that regulate the menstrual cycle. The progesterone causes body temperature to rise.

5.7.3 Pregnancy:

During pregnancy, the body temperature in women increases especially during the first three months of pregnancy. Dr. Winshall says, "There is no specific answer to explain this finding, although many things change during pregnancy, including metabolic rate, blood flow and cardiac rate, to name a few. I wouldn't be surprised if this temperature change is the result of the known 20 percent to 30 percent increase in blood flow in a pregnant woman [1]".

5.7.4 Baby's- Age less than 3 months:

Newborns are less able than adults to regulate their body temperature in cool environments. The baby's body temperature may rise when exposed to heat or when overdressed. Newborns are particularly prone to hypothermia, or low body temperature, when exposed to cold or when they are inadequately dressed. One cause for the tendency toward hypothermia is their large surface area in comparison to body weight. Heat loss occurs through the skin, so a relatively large surface area increases this process [1].

5.7.5 Old age:

Body temperature tends to decline with age. Individuals older than 65 may have an average core temperature that is 1 to 2˚C lower than that in individuals 20 years younger. Several factors contribute to changes in body core and skin temperature with age. Metabolism decreases with the aging process. This decline in the production of heat is possibly due to the declining basal metabolism together with a less-active lifestyle. The sweat glands are less active at older age and require higher body temperatures to trigger the sweating mechanisms in the skin as well is the decrease and increase of skin blood flow.

5.7.6 Alcohol ingestion:

Alcohol ingestion cause cutaneous vasodilation (which prevents vasoconstriction), impairment of the shivering mechanism, hypothalamic dysfunction, and a decrease in awareness of environmental conditions. Thermoregulatory vasoconstriction helps preserve the core temperature by preventing cooling of blood in extremities that subsequently returns to the core. Alcohol reduces or 'thins' the blood allowing flow nearer to the skin and extremities. Thus, the blood flow to the skin is uncontrolled and heatloss increased to the environment with consumption of alcohol.

5.7.7 Smoking:

The use of tobacco restricts blood circulation by reducing oxygen in the blood and constricting blood vessels, limiting blood flow to the heart. Such changes can lower core and skin temperature of the body, especially in extremities.

5.7.8 Cardiovascular and Diseases:

Cardiovascular systems and diseases influence the body and the capacity or ability of the physiological systems to balance the heat losses with production. It is the inability to deal with thermal deviations from comfort conditions.

5.7.9 Fever:

Fever produced from infection or inflammation results in the release of chemicals (cytokines) into the bloodstream, which in turn cause the hypothalamus to change the "set point" of the body for temperature regulation. In other words, fever is an appropriate increase in body temperature directed by the hypothalamus to combat infection. The most common cause of fever is a viral or bacterial infection.

"Prostaglandin's reset the hypothalamic thermostat at a higher temperature, and temperature-regulating reflex mechanisms then act to bring the core body temperature up to this new setting. Suppose that as a result of pyrogens the thermostat is reset at 39˚C. Now the heat-promoting mechanisms (vasoconstriction, increased metabolism, shivering) are operating at full force. Thus, even though core temperature is climbing higher than normal, say 38˚C, the skin remains cold, and shivering occurs, This condition, called a chill, is a definite sign that core temperature is rising. After several hours, core temperature reaches the setting of the thermostat, and the chills disappear. Now the body will continue to regulate temperature at 39˚C. When the pyrogens disappear, the thermostat is reset at normal 37.0˚C. Because core temperature is high in the beginning, the heat-losing mechanisms (vasodilation and sweating) go into operation to decrease core temperature. The skin becomes warm, and the person begins to sweat. This phase of the fever is called the crisis, and it indicates that core temperature is falling. Up to a point, fever is beneficial. A higher temperature intensifies the effect of interferon and the phagocytic activities of macrophages while hindering replication of some pathogens. Because fever increases heart rate, infection-fighting white blood cells are delivered to sites of infection more rapidly. In addition, antibody production and T cell proliferation increase. Moreover, heat speeds up the rate of chemical reactions, which may help body cells repair themselves more quickly during a disease. Among the complications of fever are dehydration, acidosis, and permanent brain damage. As a rule, death results if core temperature rises above 44-46˚C" [13].

5.7.10 Seasonal Patterns:

The normal changes of the season and the temperate climate affect the prevalence of sickness. Chronic diseases vary in frequency and severity and are sometimes only seasonable present. Minor respiratory infections such may occur as soar throats or cold during summer-winter and visa-versa changeover. Other effects are intestinal infections, fevers, heat waves, cold extremes and diseases linked with outdoors temperatures. All these have an effect on the body temperature.

5.7.11 Hot Weather

The body responds to overheating in two ways: it can decrease heat production or increase heat loss via vasodilation, sweating and lethargy.

1. In vasodilation, the blood vessels open wider and increase the blood flow to the extremities and scalp where this associate heat transfer is released to the environment.
2. With sweating, evaporation of moisture from the skin results in significant loss of heat. Sweating during a fever is a normal mechanism used to cool the body.
3. In lethargy, the body responds via slowing down to decrease heat production by conserving energy.

When heatstroke (sunstroke) occurs, the temperature and relative humidity are high, making it difficult for the body to lose heat by radiation, conduction, or evaporation, and neurological impairment has resulted. Blood flow to the skin is decreased, perspiration is greatly reduced, and core temperature rises sharply. The skin is thus dry and hot—its temperature may reach 43˚C. Because brain cells are affected, the hypothalamic thermostat fails to operate [13].

5.7.12 Cold weather

Cold weather affects the body's ability to function normally. The body responds to cold in the opposite way as to heat: it can increase heat production or decrease heat loss via vasoconstriction and shivering.

1. Vasoconstriction is the process in reverse of vasodilation. Vasoconstriction conserves heat by sending less blood to the areas of the body where heat is being lost to the environment.
2. Shivering increases body temperature by releasing heat and energy through contraction of the skeletal muscles.

5.7.13 Time of day

The body temperature is lower in the morning, due to the rest the body received and higher at night after a day of muscular activity and after food intake.

5.7.14 Body Metabolism and metabolism rates:

Each individual has his/her unique metabolic rate. Those with a slower metabolic rate may have a lower normal body temperature, whereas those with a faster metabolic rate may have a higher normal body temperature. Genetic makeup, lifestyle, the environment and many other things determine the metabolic rate. The individual's metabolic rate may change over time.

5.7.15 Hyperthermia:

Hyperthermia refers to the condition where the body temperature is above normal. When this occurs, excess heat production overwhelms the body's normal mechanism to maintain normal body temperature. The hypothalamus has a normal set point, but inadequate cooling occurs to counterbalance this heat production. An elevated body temperature increases metabolism. The central nervous system function deteriorates at temperatures above 41˚C to 42˚C [7]. At this level cell damage occur as well as neutron damage in the brain. The thermoregulatory functions and sweating cease at about 43˚C. After this, the body temperature rise dramatically and death occurs. Refer to Table 5.2 and Figure 5.1.

5.7.16 Hypothermia:

Hypothermia refers to the condition where body temperature is below normal. This is when an extreme drop in body temperature, usually to less than 35°C core temperature occurs. Hypothermia is caused by prolonged exposure to severe cold (especially when the body is wet), it may occur at temperatures only slightly below normal, after trauma, in the elderly or in individuals who are very inactive or inadequately nourished [7]. The temperature degrease reduces the chemical activity of cells and metabolism.

The thermoregulatory is impaired below 34˚C core temperature. As core body temperature declines, the basal metabolic rate and oxygen consumption drop gradually but progressively. Mild hypothermia (34 to <36˚C) results in shivering, loss of fine motor coordination, lethargy and mild confusion. At 33˚C, consciousness is lost and at 30˚C thermoregulatory fails. In moderate (30˚C to 34˚C) to severe hypothermia (below 30˚C), the pupils may dilate, and cardiovascular activity ceases. Death occurs at 28˚C due to cardiac arrhythmia and fibrillation. For the loss in Body Core Temperature, the following Clinical Findings:

- 37˚C Normal oral temperature
- 36˚C Metabolic rate increased
- 35˚C Maximum shivering seen/impaired judgment
- 33˚C Severe clouding of consciousness
- 32˚C Most shivering ceases and pupils dilate
- 31˚C Blood pressure may no longer be obtainable
- 28~3O˚C Severe slowing of pulse/respiration
Increased muscle rigidity
Loss of consciousness
Ventricular fibrillation
- 27˚C Loss of deep tendon, skin and capillary reflexes

Patients appear clinically dead
Complete cardiac standstill

Refer also to Table 5.2 and Figure 5.1.

5.7.17 Diabetes:

Diabetes mellitus is not a single disease but a multiple family of diseases. Various factors may cause diabetes, including viral infection, destruction of the B cells of the pancreas or it may have a genetic origin. Some forms of the disease involve mutations in the structure of the cellular insulin receptor or in its intracellular activities that promote glucose utilization

Mutations in insulin structure can render the hormone (insulin) inactive, and other mutations cause defects in the conversion of preproinsulin or proinsulin to the active hormone. In these cases, treatment involves administration of insulin.

The failure of insulin to act normally in promoting glucose utilization by cells, with resultant glucose accumulation in the blood, starves the cells of nutrients and promotes metabolic responses similar to those of fasting. Liver cells attempt to generate more glucose by stimulating gluconegenesis. Most of the substrates come from amino acids, which in turn come largely from degradation of muscle proteins. Glucose cannot be reused for resynthesis of amino acids or of fatty acids, so a diabetic may lose weight even while consuming what would normally be adequate calories in the diet [12].

Insulin is a peptide hormone that functions in lowering blood glucose levels. Insulin has several activities that accomplish this goal, summarized below:

1. Insulin inhibits transcription of the enzyme phosphoenolpyruvate carboxykinase (PEPCK). PEPCK is a key enzyme in gluconeogenesis and transcription is the primary means of regulating it. By inhibiting PEPCK transcription, insulin can depress glucose production tremendously. (Conversely, the hormone glucagon, which increases blood glucose levels, stimulates PEPCK transcription.)
2. Insulin stimulates translocation of the glucose transporter protein from cytosol to the cell surface. Glucose transport protein carries out the facilitated transport of glucose.
3. Insulin stimulates phosphatase activity that removes phosphates from molecules activated by the kinase cascade [12].

5.7.18 Starvation or Fasting:

Fasting implies going without food for a few days while starvation implies weeks or months of inadequate food intake or malnutrition.

A normal human body can store the equivalent of 6700kJ of energy as glycogen. This source of blood glucose can be exhausted or used as energy just a few hours after a meal. During starvation, the body adapts metabolically to increase the use of fuels other than carbohydrate.

According to Mathews, van Holde, and Ahern, the body stores about 565,000kJ as triacylglycerol largely in adipose tissue, and 100,000kJ as mobilizable proteins, largely in the muscle. These stores provide sufficient energy to permit survival for up to several months, but the compounds must be modified to be of use [12].

The metabolic changes accompanying starvation compromise the organism's abilities to respond to further stresses, such as extreme cold or infection. However, the adaptations do allow life to continue for many weeks without food intake, the total period being determined largely by the size of the fat deposits in the body and the environmental conditions being exposed to.

5.8 The Normal Body Temperature and Thermal Neutrality

On focusing on the neutral zone and the thermal balance, the skin blood flow relates to the four parameters of control and the erroneous belief of interpreting altered equilibrium temperatures as the consequence of changes in 'set point'. The possibility exists that the body core temperature in the neutral zone might remain constant over a wide range of skin temperature difference, or even rise when skin temperature falls, or the may also occur in reverse.

If the parameters of skin temperature control are just correct, the physical and reflex effects of a skin temperature change could combine for no net effect on the core temperature. This is possible due to the reflex effects of the skin temperature changes interaction with the associated change in core to skin temperature gradient temperature. This gradient is vital to heat transfer and imply for the phenomenon named 'afterdrop'.

Normal body temperature is an equilibrium core temperature in conditions of thermal neutrality. However, a constant body temperature does not imply thermal neutrality. The concept of normal body temperature and thermal neutrality is limited to the environment in which a normal person at rest can achieve an equilibrium core temperature without resorting to shivering or sweating.

Thermal neutrality exists in a broad range of environments. For instance, the body core temperature can stabilize in a near naked person in a hot dry environment without the necessity of sweating (for cooling). At the other extreme, thermal neutrality can exist in a person in below freezing environment conditions due to heavy clothing that maintains the environment next to the skin similar to neutral temperature conditions.

The core temperature will remain constant in both these environment conditions as long as the thermal conditions and metabolic rate do not change. Therefore, extreme ranges of air temperatures compatible with thermal neutrality contrasts with a narrow range of skin temperatures exists. Based on physical measurements, or analyses of thermal balance in terms of skin temperature, the neutral zone is likely between 33˚C to 35˚C.

The range of thermal neutrality agrees to nearly the same range of body skin temperatures. See Table 5.5 below. In order to find the neutral zone of human body temperature regulation MV Savage and GL Brengelmann subject themselves to 'dozens of experiments in which thermal balance was analysed by means of a calorimeter in which they were exposed for long periods to controlled ambient conditions. They observed that total heat production and total heat loss came into equilibrium only in the range of calorimeter temperatures indicated. On the high side, they sweated. On the low side, they shivered. In between, the associated range of skin temperature was approximately 33 to 35 °C' [10].

	Peripheral Insulation	Peripheral Blood Flow
Core Temperature T_c	37°C	37°C
Skin Temperature T_{sk}	33°C	35°C
Difference ($T_c - T_{sk}$)	4°C	2°C
Insulation	thick	thin
Skin Blood Flow	low	high

Table 5.5 Study of the Neutral Zone [10]

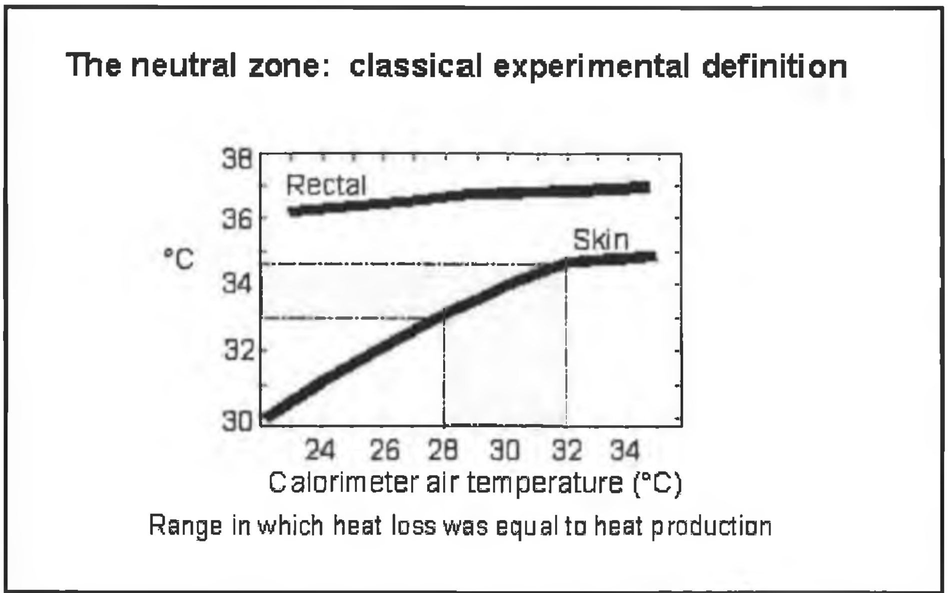


Figure 5.3 The neutral zone experimental definition [10]

The above Figure 5.3 emphasises that the findings indicate that the body's insulating layer is variable. The difference between core and skin temperature is only 2°C at one end of the neutral zone and at least double at the other end. 'To have the *same heat transfer* for a *factor of two difference* in temperature gradient, the effective insulation of the shell of peripheral tissues that surrounds the body core must differ by a factor of two' [10]. This variable insulation is due to modulation of peripheral blood flow.

Major progress in the prevailing years has been the recognition that blood flow is changing to vary heat transfer and change the effective insulation of the shell is the blood flow in the skin. The skeletal muscle is the only vasculature that might participate and is unaffected by the influence of thermally driven reflexes that alternates skin blood flow.

5.9 Body Thermoregulatory Control in Reference to Skin Temperature

A delicate balance between heat-producing and heat-losing mechanism in the body maintains normal core temperature. The very simplest view of the mechanism of body temperature regulation is that it responds to more than one input that affect the state of the effectors. The following type controllers is possible in temperature regulation for the body:

1. Thermal actuated switch, or
2. Temperature proportional controllers.

The thermal actuator switch principle works on an 'on-off' adjustable points operation usually with a temperature fixed set point. As references, the body uses 'on-off' points to react to the temperature at which the switch is activated. The body governs the heat loss and gains via skin blood flow around these parameters set by the thermal actuated switch. The operation of this regulator always oscillates and forms a pattern around this set point where the body switches 'on' and than 'off' in trying to reach the thermal balance. Another consideration is when the set point or body thermal load changes. This form of thermoregulatory control conforms least to the behaviour of the body.

The next consideration is temperature proportional controllers nearer to the explanation of the complexity of the temperature regulation system in the body. The equilibrium temperature is not, in general, equal to the set point temperature. While this principle does not have a set point and have the advantage that it does not oscillate, it functions on the basis of control signals and temperature sensors. The 'sensor' initiates blood flow progressively in relation to the maximum requirement by the temperature controller. This proportional control is therefore through temperature gradients.

The drawback of this arrangement is that the temperature sensor is really controlled and therefore the positioning of these sensors is vital for correct temperature sensing. This principle also does not equilibrate at the set point and this generates an error signal on the thermal load. It takes more than the evidence of altered equilibrium temperature to justify the interpretation that the set point has changed.

5.10 The Equilibrium Temperatures, Error Signals, and the Body Set Point

The influence of external ambient conditions effect the body thermo output in terms of heat loss. The body heat loss behaviour requires being 'predicted' in order to ensure the continuous operation of the TE Collar in diverse 'body conditions'.

The thermal behaviour in a relatively warm environment requires little heat to keep the body comfortable. If the environment cools, the consequent tendency for body temperature to fall causes increased heat output. Without a temperature controller, the body temperature would simply follow environmental temperature. The body temperature controller would be higher than the environmental temperature if the body heating system were set at a fixed level, but would equilibrate at a fixed increment above environmental temperature. With the body heat system output adjusted by a proportional type controller, temperature of the core body still follows environmental temperature but the core body temperature changes less than environmental temperature. How much less depends upon the proportionality between the body core temperature and body heat output. This proportionality is called the gain of the controller. The bigger the gain, the greater the increment in effector output for a given change in sensed temperature.

In practice if the gain of the body temperature control system is set too high it is likely to oscillate because of the lag in time between application of heat transfer and achievement of a stable temperature in the body. To be specific about the equilibrium following the change in environmental temperature, the new equilibrium is determined by the controller property in relation to the additional load imposed by the environment.

That rate of heat loss is driven by the difference between the body core temperature 'T_c', and the outside temperature. The temperature remains constant at 'T_c' because the rate of heat output set by 'T_c' is exactly the right rate to balance the heat loss driven by the gradient between 'T_c' and outside temperature 'T_a'.

The amount of the offset from the equilibrium and 'T_c' is called the error signal. The bigger the thermal load imposed by the environment, the bigger the error signal, sometimes called the load error. If 'T_c' is taken as the set point, then the load error is the difference between the equilibrium temperature and the set point. These terms are used in discussions of human temperature regulation. For example, the elevated core temperature maintained during exercise has been described as representing a load error. This elevated temperature is required to activate the physiological defences.

The change in equilibrium temperature indicates that it is obviously not due to a change in set point. Nothing in the controller properties changed, only the equilibrium temperature and body heat output. Probably no one would make the mistake of interpreting an observed change in equilibrium temperature as due to a change in set point in a situation where the change in environmental conditions disturbed the initial equilibrium. It is when equilibrium temperature changes under fixed environmental conditions like the fall of metabolism when the body relaxes or requires energy. However, the change in equilibrium temperature can equally occur as a consequence of altered gain.

The changes in equilibrium temperatures in the human body, are far more complex than to allow the singling out of one parameter that might be changing. The body temperature regulator and the thermoregulation process are more complicated than the simple proportional control system explained above. Our effector systems are influenced by skin temperature as well as core temperature.

'However, at least in some regions of control, its behaviour (the body temperature) compares to that of a dual-input proportional controller. In such systems, two control loops feed back information on temperature to the functional unit that controls effector output [10]'.

In principle, if you could hold skin temperature constant at 38°C and gradually elevate core temperature from a low level, the vasodilator response would first occur at a certain threshold and increase proportionately thereafter.

The Equation 5.20 illustrates dual control based on research findings on control of skin blood flow in the hyperthermic zone where active vasodilation in the skin occurs along with sweating. Skin temperature acting as an independent influences on the effectors and is expressed in the equation that the effector output is the sum of independent contributions driven, respectively, by core temperature and by skin temperature.

Neutral zone temperature regulation may be express by:

$$SkBF = a(T_c - T_{co}) + b(T_{sk} - T_{sko}) \quad (5.20)$$

Where 'SkBL' is the skin blood flow. Thermal balance occurs in the SkBF influenced by the body core temperature 'T_c' and the skin temperature 'T_{sk}' results in delivery of heat to the surface at a rate that matches the metabolic heat production (less respiration heat loss). The balance is upset by changes in:

1. Core temperature gain;
2. Core temperature reference level, 'T_{co}';
3. Skin temperature gain; and
4. Skin temperature reference level, 'T_{sko}'.

It is unknown if control of skin blood flow in the neutral zone will work like control in the hyperthermic zone. The flow levels are much lower in this range where flow is presumably modulated only by vasoconstrictor tone rather than through active vasodilation. However, the simplest assumption that we can make is that control in the neutral zone is another one of these dual-input proportional systems and it might be approximate quantitatively by the equation repeated in the graphic panel. Thermal balance will occur when the skin blood flow is at exactly the right level to deliver the right amount of heat to the body surface. The particular levels of core and skin temperature set that level of skin blood flow.

This relationship has four parameters, two more than the simple proportional control system described in previous pages. If any of these were to change, then the equilibrium core temperature for a given skin temperature in the neutral zone would change.

If a change in equilibrium core temperature is observed in a person in neutral thermal conditions, this is not a change in set point. The possibility exists that skin temperature or any of four parameters, might have changed. It might be better explained as two separate 'gains', one the sensitivity to core temperature, the other the sensitivity to skin temperature; and two separate 'set points', one the core temperature reference, the other the skin temperature reference. To conclude, change in equilibrium core temperature occurs when the thermoregulatory 'set point' has changed because skin blood flow does not belong exclusively to temperature regulation. It belongs to cardiovascular system regulation as well. The interaction between cardiovascular regulation and thermal regulation could be through any or all of these four parameters.

According to Savage and Brengelmann, 'Probably the worst example of fallacies that arise from the core temperature set point idea is the tendency to think that some sort of constant reference must exist in the nervous system, against which core temperature is compared. What is necessary for a stable thermoregulatory system in which the same equilibrium core temperature exists under the same thermal conditions is simply a fixed functional relationship of effector output to core temperature and skin temperature (and other variables such as those related to cardiovascular changes). In nature nothing decrees that a fixed input-output functional relationship in a physiological control system rely upon some kind of neural device that compares a fixed reference to the stream of input information derived from the body's temperature sensors [10].

It is simple enough to enable working out estimates of how the reflex effects of changes in skin and core temperature interact with the physical effects. This kind of analysis leads to a surprising prediction. Given the right ratios of parameters, core temperature might be independent of skin temperature in the neutral zone or even change in direction not expected, for instance, the rise of core temperature when skin temperature drop and vice versa.

The difference between core 'T_c' and skin temperature 'T_{sk}', interacts physically with the total skin blood flow. The greater the difference between 'T_c' and 'T_{sk}', the greater the amount of heat transferred to the body skin surface. The heat transfer is therefore proportional to the product of the temperature difference and the blood flow.

'A change in either 'T_c' or 'T_{sk}' affects heat transfer through the effect on the (T_c - T_{sk}) difference and also skin blood flow, through the thermoregulatory reflex influence of both 'T_c' and 'T_{sk}'. A change in 'T_{sk}' that reduces the temperature difference (a change in the direction of reducing heat transfer) would simultaneously induce an increase in skin blood flow (a change in the direction of increasing heat transfer. Arrows in the diagram show effects of an increase in skin temperature' [10].

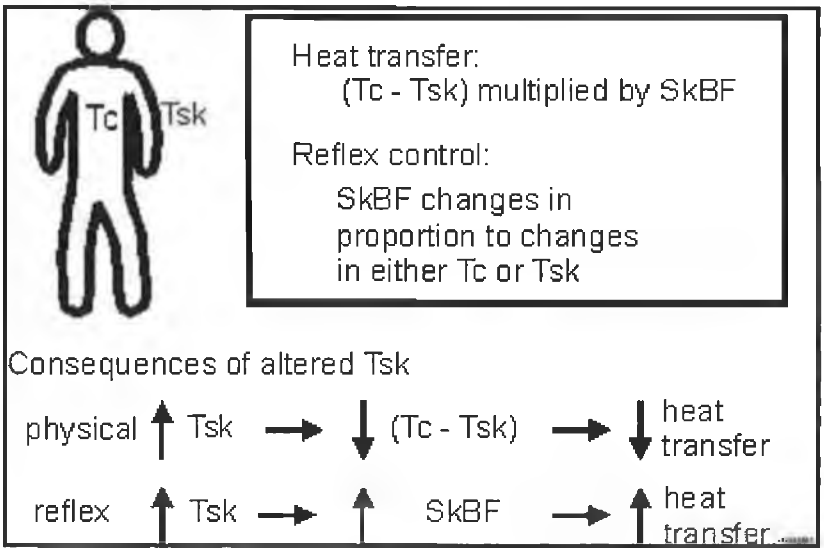


Figure 5.4 Consequences of altered Skin temperature [10]

The first line is the physical effect. The increased in the skin temperature decreases the difference between core and skin temperatures. Consequently, less heat is delivered to the skin surface by a given amount of skin blood flow. The bottom line is the reflex effect. Increased skin temperature increases skin blood flow with the consequence of increased heat transfer. The two effects could balance each other out. If the gradient was reduced by, say, 30% percent and the increase in blood flow also 30%, the net effect of the skin temperature change on heat transfer could be zero. Core temperature would remain steady despite the changes in skin temperature and skin blood flow.

If the physical and reflex effects did balance one another, skin temperature could be driven from one extreme of the neutral zone to the other with no effect on core temperature. The whole process of regulation of thermal balance would be accomplished through this reflex control from skin temperature that perfectly balanced the physical effect of the altered gradient.

While the core is maintained at fairly constant temperature (see Figure 5.5) the shell varies in temperature with a gradient to the surface. The depth of the body shell also varies according to the body's existing thermal state.

If the effects do not balance, then core temperature will seek a new equilibrium after a skin temperature change. It is expected that the core temperature should follow suit to the skin temperature. It would however not be possible if the reflex reduction of skin blood flow were proportionately greater than the increase in core to skin gradient. Core temperature would change the wrong direction - it would increase in response to a decrease in skin temperature.

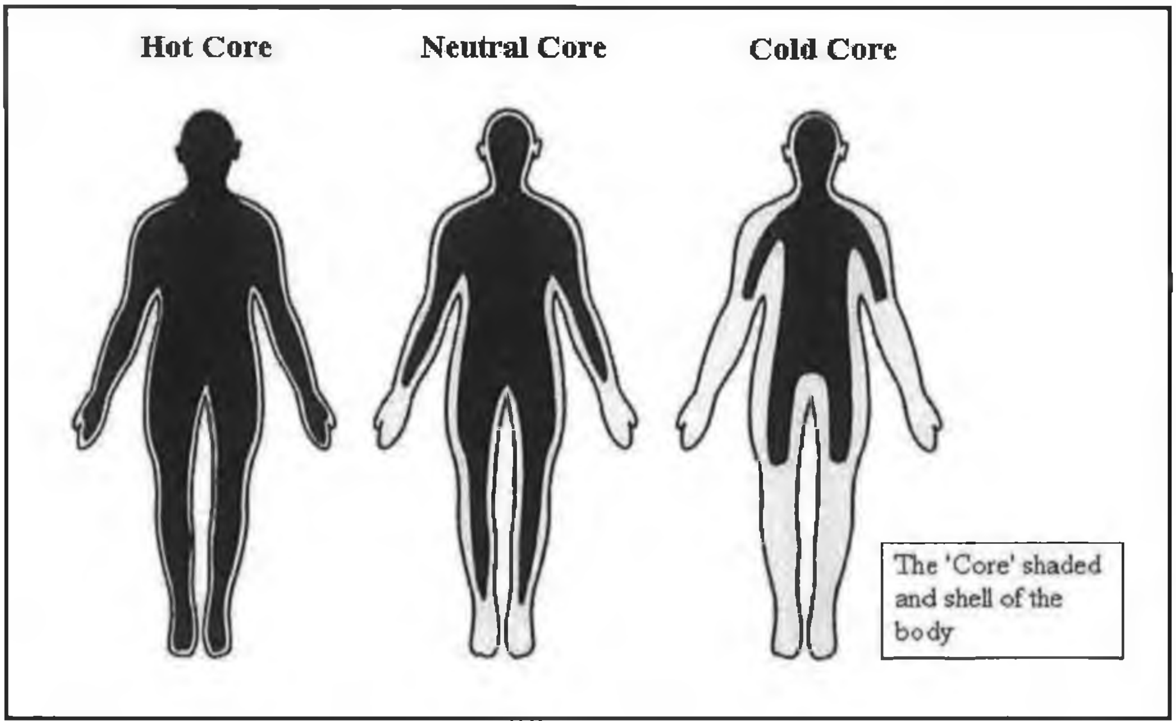


Figure 5.5 The body 'core' and shell [11]

'Afterdrop' is a familiar phenomenon in which core temperature falls when skin temperature increases. 'Afterrise' is a phenomenon less observed. The observation that a sudden drop in skin temperature causes a rise in core temperature is usually at skin temperatures far outside the neutral zone.

Core temperature need not be affected by the skin temperature changes thanks to appropriate, skin temperature-driven adjustments in skin blood flow.

The skin makes up about 5% of total limb volume. The estimated total skin blood flow change is consistent with estimates of the flow levels necessary for the transfer of body heat to the skin surface.

5.11 Considerations on the Impact to the Body utilising MPTG

The difficulty with in using heated or cooled devices at the proposed areas may result in different symptoms depending on the individual. To cool down or conduct heat away from the neck main arteries may generate a feeling of dizziness or loss of control and direction.

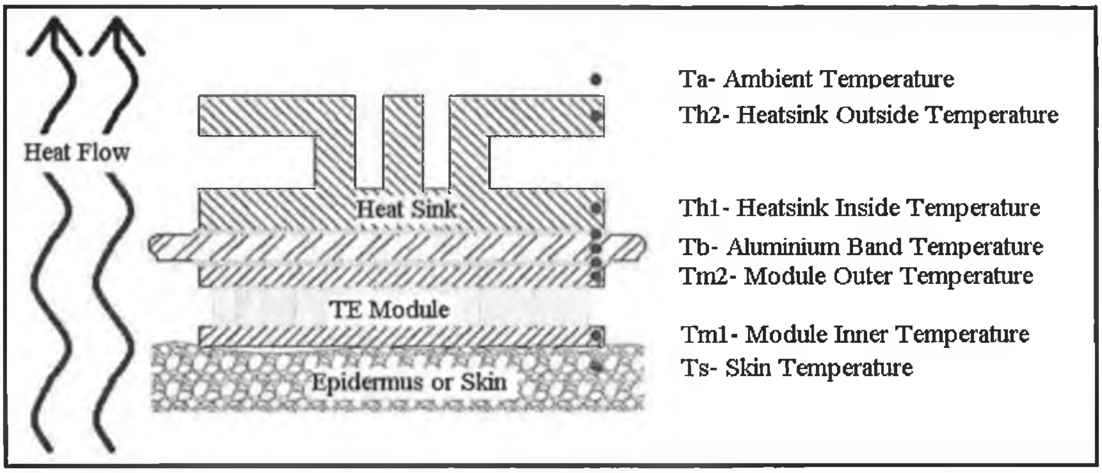


Figure 5.6 Schematic of Temperature points through the heat transfer process

Directing energy in the form of heat away from the head would cause the body to produce additional heat to balance this heatloss. The magnetism interference on the body's natural magnetism fields may be disrupted with a MPTG and result in nerve disruptions or degrading. Other considerations include restrictions on blood flow, claustrophobic feelings, restriction on swallowing, neck movement, friction between the MPTG and the neck skin. The effect of electricity and the presence of TE modules on the body and senses may be considered as external influences and need to be studied in more detail and for future considerations.

5.12 TE Collar Squeeze

The drawback in utilising the TE Collar is in the squeeze experience at the neck. Since the main arteries are connected via the neck to the brain, this squeeze restricts or clamp down on the arteries and lower the blood flow supply to the brain. Scuba divers experience the same form of minor squeeze via tight wetsuits.

5.13 Skin Irritation due to friction

The TE Collar may cause sin irritation due to the friction of the metal to the skin. The metal is in continuous contract to the skin to utilise the heat and therefore the flexibility as well as movement from the neck and body e.g. walking or running cause friction. Since the Collar is a rigid object on a flexible surface, this irritation may vary from person to person.

The absorption of the skin (the passage of materials from the environment into body cells) penetrates the epidermis and dermis as lipid-soluble materials. Greatest skin absorption occurs through the scrotum, head, face, and neck, and when skin is damaged or covered with clothing following exposure. Children have a greater skin surface area relative to their body weight than do adults and exposure to harmful materials would receive a greater dose relative to body weight than an adult with the same exposure.

Toxic materials can be absorbed through the skin include organic solvents; salts of heavy materials like lead, mercury and toxins. Exposure over time and in a certain quantity of exposure affects the body health system [13].

5.14 Conclusion

Harvesting energy from the body is not a new concept. The challenge is to develop the correct application to be utilised externally (to the body). The body naturally generates heat, movement, electrical impulses, wave energy and magnetism. All these may be used as energy sources. Although all of them have been studied in depth, no feasible and commercial application has been forthcoming. With thermoelectric applications, this might now be possible.

Finally, colloquial words and phrases like, "You are on fire", "I'm burning", and "You are hot" might all be pointing subconsciously in the same direction and conclusion. We all have our own internal furnace, a heat source to be utilised for our own generation applications. We just require the correct means to tap to that source.

Chapter 6- Thermoelectric Generation Impact

6.1 Introduction

Energy usage is associated with obvious defined benefits. Therefore, the amount of energy spent in order to extract that benefit depends on the process used. According to Bent Sorensen [2] "the finale benefit is the same, but the amount of energy spent is a function of the level of technology, and of whether an effort is made to use energy efficiently or not." Therefore developing renewable sources of energy reduces environmental impacts, increases energy efficiency and increases the reasons that compel energy consumption.

Energy usage can be categorised in three basic categories:

1. Human environmental comfort- heating, cooling and food;
2. Heat for light and manufacturing; and
3. Force applied to create movement and transportation.

Energy impacts on everyday life and contributes to the nation's wealth, prosperity and security. The energy industry output contributes to the GDP (Gross Domestic Product), national economy and creates growth opportunities and employment. This chapter focuses on the thermoelectric impact on the environment, production, distribution and use of this energy generation.

Regions: Qualification of Energy Delivery	1.USA/ Canada	2.Western Europe, Japan, Australia	3.Eastern Europe, Russia, Middle-East	4.Latin America SE Asia	5.China, India, rest of Asia	6.Africa	Average/ Total
Food- Animals	30 45 17	30 45 24	30 45 47	25 37 52	25 37 148	20 25 51	26.67% 36 W/cap 339 GW
Food- Grain/ Vegetables	70 119 45	70 119 63	70 119 124	75 128 177	75 128 506	80 114 232	73.33% 123 W/cap 1147 GW
Transportation	359 136	299 158	140 146	201 277	99 392	30 61	125 W/cap 1170 GW
Low Heating/ Cooling	103 39	110 58	87 90	43 60	80 318	22 45	65 W/cap 610 GW
Environmental Heat	240 91	256 135	203 210	100 140	186 741	51 105	152 W/cap 1422 GW
Appliances	420 153	424 224	245 255	288 398	283 1116	47 96	240 W/cap 2242 GW
Total delivered Energy	1272 482	1252 661	838 871	800 1104	814 3225	290 591	743 W/cap 6934 GW
Estimated Population 2050	379	528	1040	1380	3960	2040	**9327 mil**

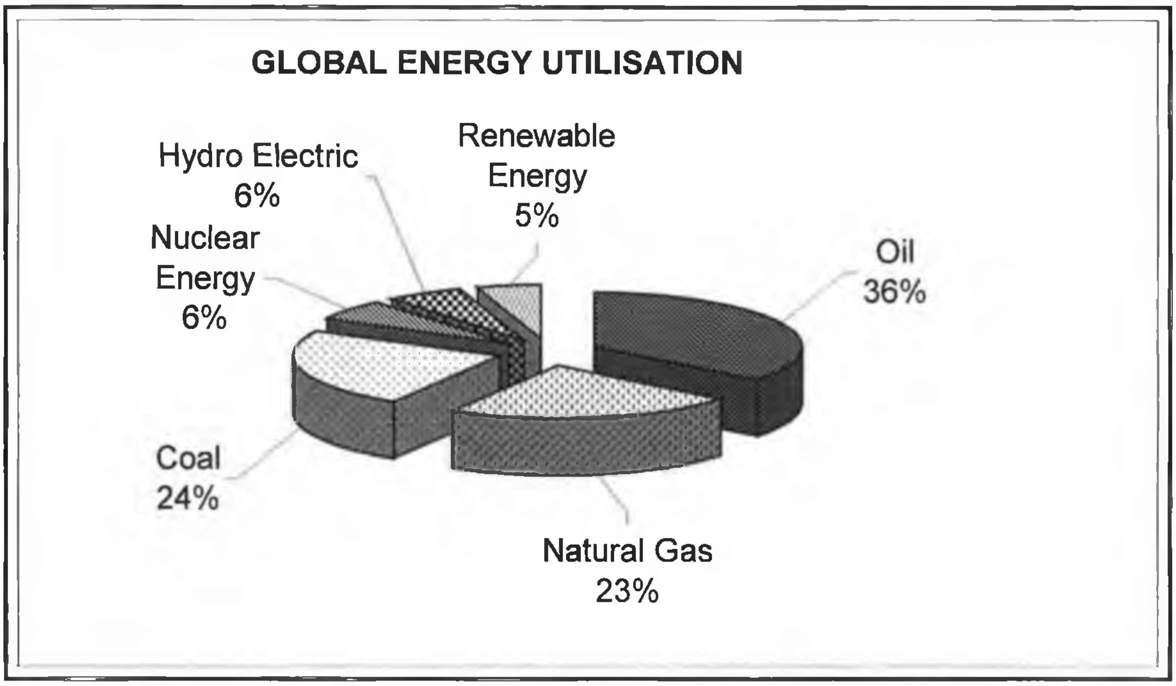
Table 6.1 Energy Delivered in 2050 adapted from Sorensen and Meibom (1998)[1]

Table 6.1 above indicates the 2050 scenario of the projected energy requirements. Although the author does not agree with these projected figures as epidemics (like AIDS), famine, wars, natural disasters, reduced resources and economic depression are not brought into the estimation, the energy requirements can form a guideline in the use of energy consumption and utilisation to ensure future global stability in energy management.

6.2 Thermoelectric Generation as a Renewable Energy

Thermoelectric Generation is considered as a renewable energy conversion or a reversible process. A nonrenewable or irreversible energy conversion depletes or exhausts certain materials or fuels of the earth without adding or replenishing the source. Generally irreversible energy processes forms a by-product (such as CO_2). These by-products are harmful to the environment as fuels where materials are broken down to form energy or increase entropy. Entropy is part of the system and quantifies the amount of energy available in the system.

With renewable energy, the energy is utilized from inexhaustible sources continuously available and sustainable in our environment (wind, solar or ocean) or with the replenishable sources (Bio-mass). The advantages of renewable energy are that it provides security of energy supply, is environmentally friendly and contributes to global energy price stability. In particular to greenhouse gas emissions, renewable energy's are emission neutral over their life cycle.



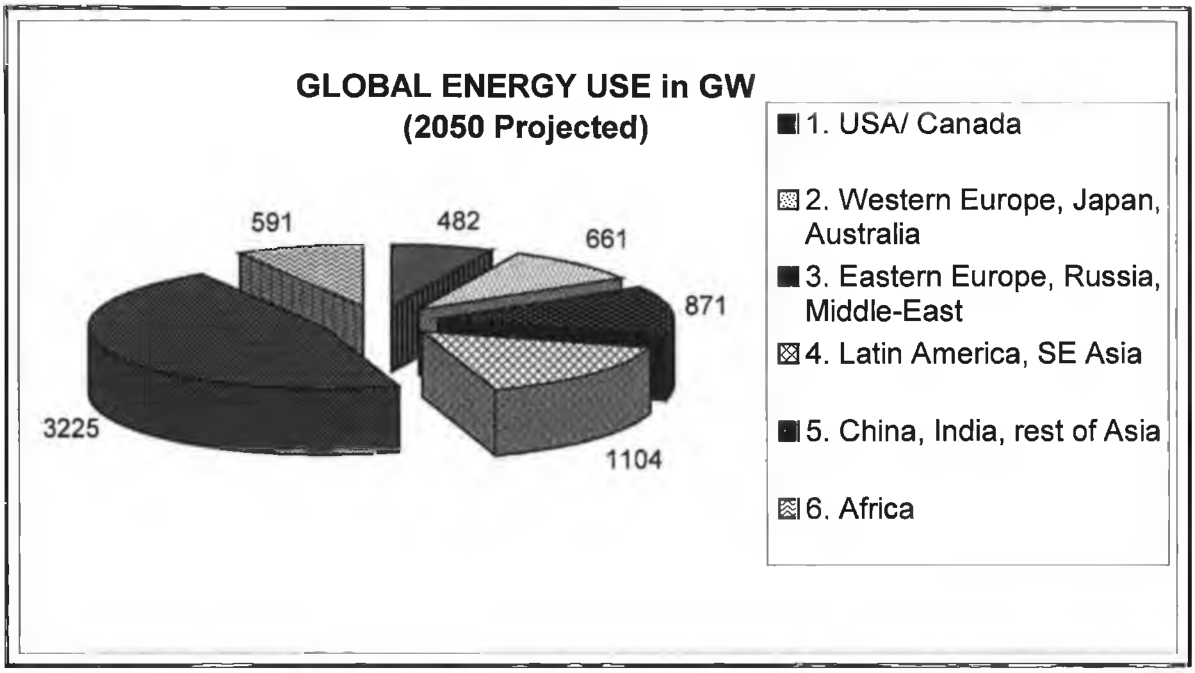
Graph 6.1 Global Energy Utilisation adjusted from BP Statistical Review of World Energy [3]

The major renewable energy sources categories are: Solar, Wind, Biomass, Hydrogen, Hydroelectric, Geothermal and Ocean energy. From Graph 6.1, the 5% Renewable Global Energy Utilisation, less than 0.5% is made up of Thermoelectric, 8% Solar, 68% Biomass, 10% Wind, 6% Geothermal, 8% Ocean Energy sources. Apart from thermoelectric energy in this thesis application, all of the above renewable energy sources are solar-derived technologies or in some way influenced by the sun and the transformed energy from the sun (in the earth's surface, atmosphere, oceans, photosynthesis, or the evaporation of water.)

6.3 Thermoelectric Generation Energy Scenario

The demand for energy in the form of electricity is already established. What remains is to determine in what manner and what type of source is to be use to meet this demand. Thermoelectricity in the market sector forms a very small segment of the global energy supply (see Graph 6.1).

The International Energy Agency (IEA) projects that the world's electrical generating capacity will increase to nearly 5.8 million megawatts by the year 2020, up from about 3.3 million in 2000[5]. To date, the main supply of electricity generation is from fossil fuels, predicted to end between the years 2020 to 2050. To meet this electricity demand, a gradual changeover to a sustainable energy source like renewable energy is required. It is estimated that renewable energy will supply 60% of the world's energy by 2060[5].



Graph 6.2 Projected Global Energy Use in Giga Watt in 2050, adjusted from Sorensen and Meibom (1998)[1]

The systematic changeover in fuel usage has been responsible for a large portion of carbon dioxide reduction. Gas and nuclear power have been used to replace fuels such as coal and oil that emit more pollutants per unit of energy burned. Not only the changeover, but also improved efficiency has reduced the carbon dioxide emissions from power stations.

Furthermore, the introduction of legislation and new technology like combined heat and power (CHP), has helped to reduce emissions. Nuclear power contributed 6% of the global electricity supply. Although a source of carbon free electricity, it is currently economically unattractive. Issues on the disposal of nuclear waste and security risks have yet to be resolved. Although nuclear power has generated electricity safely for nearly 50 years and with the nuclear industry tightly regulated for both operational safety and environmental impact, it is an energy source being phase out [5].

This brings us to renewable energy as the next step in the supply of electricity. Therefore, thermoelectric generation will increase as fossil and nuclear energy sources are gradually replaced.

6.4 Thermoelectric Generation Conversion

The energy desired is electricity and the initial energy form is heat. Thermoelectrics conversion is a direct conversion process. It utilise heat from a variety of possible sources on the surface of a TE module hot side and transfer to a lower temperature at the opposite surface or cold side. TE modules are constructed to ensure as much of the available heat as possible is transferred through the module in order to create a temperature difference. With this temperature difference maintained across the module, electrical power is generated. (See Chapter 3 & 4)

To date, thermoelectric generation is most commonly used in waste heat applications as a renewable energy or to increase power generation plant efficiencies. Due to its inherent characteristics and obvious advantages in size and applications, it increasingly becomes popular as a rediscovered technology in the energy market. Not only is the process in itself safe and feasible, but it is also low cost and a lack of harmful emissions make this renewable technology extremely attractive.

With renewed interest in TE technologies as well as in renewable energy sources or hybrid combinations, new discoveries will ultimate change the future of energy supply.

6.5 Thermoelectric Generation Environmental and Social Impacts

There is an increased awareness to the danger and damage caused by pollution. The pressure has increased to become more environmental responsible. The environmental impact of electricity generation is largely dependent on the choice of fuels that are used for generation. Fossil fuels produce greenhouse gas emissions impacting on local air and water quality, damage to forests and depletion of the ozone layer while nuclear generation results in radioactive discharges into the air and water.

Although utilization itself has no direct environmental impact, increased consumption requires increased electricity generation with greater overall environmental impact. Efficient use of electricity and selection of fuel source is therefore an important and effective way to reduce environmental impact of both its generation and supply. See Table 6.2 below.

There are several environmental benefits in the use of renewable energy. Where fossil fuels contribute significantly to many of the environmental problems e.g. greenhouse gases, air pollution, and water and soil contamination, renewable energy sources contribute somewhat or not at all.

Ultimately, renewable energy can change the conventional utilisation of energy to improve the quality of our environment and improve the efficiency of energy usage.

	Impact Type: Emissions (g/kWh)	Uncertainty	Monetised Value Euro/kWh	Uncertainty & Ranges
Environmental Impacts: Usage of Thermoelectric energy in power conversion				
Ozone impact	NA	L	0	L, r, n
Greenhouse warming	NA	L	0	L, r, n
Noise	NA	L	0	L, r, n
Land use	NA	L	NQ	L, r, n
Visual Intrusion	NA	L	NQ	L, r, n
Social Impacts: Occupational Injuries				
1. In usage		L	0	L, r, n
2. From manufacturer		L	0	L, r, n
3. From construction and decommissioning		L	0	L, r, n
4. From operation		L	0	L, r, n
Occupation health & injury				
Diseases	NA	L	0	L, r, d
Accidents	NA	L	0.005*	L, r, d
Transport	NA	L	0	L, r, d
Operation (injury)	NA	L	0	L, r, d
Economic Impacts:				
Direct cost at present			0.03*	
Resource use		L	NQ	
Energy payback time	2y	L	NQ	
Labour requirements	NA	L	NQ	
Benefits from power sold			0.03-0.05*	
Other Impacts:				
Supply security (plant availability)	high		NQ	
Robustness (Technical reliability)	high		NQ	
Global issues (non-exploiting)	compatible		NQ	
Decentralisation & consumer choice	good		NQ	
Institution Building (grid required)	modest		NQ	
(L,M,H): Low, Medium, High uncertainty. (l, r, g): local, regional, global impact. (n, m, d): near, medium, distant time frame, NQ-not quantified, NA not analysed. * Estimated figure				

Table 6.2 Impacts from Thermoelectric usage

6.5.1 Thermoelectric Generation- Greenhouse Gas Emissions and Air Quality

One of the major causes of climate change is the increased level of greenhouse gas emissions to the atmosphere. The 'greenhouse effect' is due to the constant supply of carbon dioxide (CO_2) and other gases into the atmosphere. Gases absorb infrared (IR) light and heat (which is infrared radiation). These are gases consisting of two different kinds of atoms, such as the mentioned CO_2, but also CO, NO and all carbon hydrogen's (HC) such as methane, propane or other natural gases employed for heating. IR light is capable to excite higher energy levels or excited states of the molecules (rotational or vibrational excitations) by coupling to the dipole moment of the heteroatomic assembly. Heat energy from the IR light is therefore transferred into the gas and heat up these gasses.

Due to the increased use of fossil fuels (yearly increase of coal 6.9%, gas 2.8% and oil 0.1% [3]) it significantly increased greenhouse gas emissions, particularly carbon dioxide, creating an enhanced greenhouse consequence. It is estimated that carbon dioxide is responsible for more than half of the contribution to global warming.

The long-term effect associated with global warming is on the weather and climate as temperatures can increase or decrease causing to extreme weather patterns and climatic change across the globe.

The air quality impacts on every day life and create health issues. Air pollution can be defined as fine, suspended particles in the air that are derived from a wide range of man-made and natural sources, including incomplete fuel combustion, atmospheric chemical reactions, wind-blown soil or dust generated by activities such as quarrying or agriculture and fires. Both pollution and global warming create major health, safety, and air quality problems to humans. Air pollution is a major contributor to lung disease and includes asthma, lung cancer, respiratory diseases and infections

Nitrogen compounds including nitrogen dioxide, nitric oxide and nitrogen oxides are formed in combustion processes when nitrogen in the air or the fuel combines with oxygen. These compounds then combine with water in the atmosphere to form sulphuric and nitric acid and add to the natural acidity of rainfall. Ecosystems including soil, crops, freshwater, lakes and streams are also polluted with acid rain due to air pollution

The biggest contributors of carbon dioxide emissions are: Power stations (29%), Industry (23%), Transportation (22%) and the Domestic Sector (16%). Carbon emissions are derived from the incomplete combustion process of fuel. Carbon dioxide emissions relate to the type and amount of fuel burned and its efficiency of use. Most power plants and industry use either coal or gas (refer to Graph 6.1) where oil or petroleum products are readily used for transportation. The domestic sector uses fuel according to commercial and economical attractiveness. Due to the continued increase in the summative electricity consumption, carbon emissions rise but is compensated and even reduced according to the share of electricity generated from renewable sources allowed by international legislation.

Renewable energy technologies can produce heat and electricity with very low or no amount of carbon dioxide emissions. Thermoelectric energy is therefore considered a clean energy. The advantage of TE systems is that they do not require evaporative chemicals that may be harmful to the environment. Other chemicals like lubrications, oils or chemicals for moving parts or insulation is not required. Apart from the energy source, TE modules used in TE generation is completely safe and unique in operation from other devices. Although roughly similar to solar cells in application, its generation method differs completely.

The National Climate Change Strategy (NCCS), has outlined a strategy to meet Ireland's commitment to limit greenhouse gasses emissions to a 13% increase over 1990 level by 2008 according to Kyoto Protocol. The strategy includes [4]:

1. Reduction of CO_2 emissions by 1million tons by 2010 through increased deployment of renewable energy (RE).

2. Review of rate and structure of energy taxes.
3. Fuel switching towards less carbon intensive sources including RE.

See Addendum, Chapter 11, Item 11.4 for Pollutants

6.5.2 Thermoelectric Generation Construction Impact

The TE Collar is constructed in three stages (modular construction) in accordance with the concept of progressive generation. The construction assembly of the complete TE Collar or Miniature Personal Thermoelectric Generator basically consists of the following activities: (i) design and CAD work, (ii) setting out of modules and heat sinks, (iii) laying of module and heat sink base, (iv) mechanical assembly work, (v) electrical assembly work, (vi) equipment and final connections.

The layout of the TE Collar was designed to facilitate its construction in three distinct stages, considering an installation sequence that first involves the thermoelectric generation equipment, followed by heat and cold sinks and then the electrical DC-DC converter. The combined operation cycle involved the TE Collar as the energy converter from heat to electricity and then the conversion process from the DC-DC converter to the operational output voltages. The visual impact of the design depends on the individual and whether the individual utilises the TE Collar in the neck or other positions.

6.5.3 Thermoelectric Generation- Auxiliary Systems Impact

Apart from the manufacturing plant, TE Collars require no supplementary systems to supply electricity or to ensure protection of the system or TE Modules. Auxiliary systems including a water-cooling, diesel oil and natural gas, water treatment, liquid effluent treatment, boilers, chemical products dosage system, fire dosing or protection may be required at the manufacturing plant

6.5.4 Thermoelectric Generation- Fuel / Energy Impact

Thermoelectric energy make-up is less than 0.000025% of the global and 0.05% of the renewable energy sector (see Graph 6.1). Most of the world's resources are situated in certain regions such as, the oil reserves in the Middle East (about 60%), the gas fields in Russia (about 40%) and Middle East (about 40%). The shift in economic influence through the last three sharp increases in the world's oil prices: the Arab Oil Embargo in 1974, the Iranian Oil Embargo in 1979, and the Persian Gulf War in 1990 has resulted in periods of negative economic growth and a rising trade deficit [2 & 6].

The requirement to explore and develop existing renewable energy source is evident. Every country depends on a secure form of energy provision for economical and national security. The dependency on conventional fossil fuels is vulnerable to political instabilities, trade disputes, embargoes, price fluctuations, and other disruptions. To decrease the dependency on fossil fuels would decrease foreign imports and increase renewable energy usage. This in effect will reduce environment emissions.

One major difficulty in switching to renewable energy is that existing fossil fuel supplies are convenient, cheap and relatively abundant. Other factors include easily shipment of bulk at minimum cost due to high energy density, they can be easy stored and are widely available and used.

In this thesis, body waste heat or the body as a heat source is utilized for TE generation. In itself it would not significantly impact on the global or even national market energy utilization, but in principal, will reduce waste and emissions and reduce the dependency on fossil and chemical fuels by the consumer market. The advantage of a renewable energy source is their security, inexhaustibility and diversity.

6.5.5 Thermoelectric Generation Legislation

The legislation regarding environmental impact by the EU countries has outlined the conditions for renewable energy in its draft Renewables Act. In Germany, the law aims to increase renewable energy usage from the nation's current 6% to 12.5% by 2010. Germany's legislation has influenced other countries such as Austria, France, Spain and Czech Republic to consider similar initiatives by their own governments. In Ireland, the Carbon Law is due to come into effect in 2004. In order to meet international requirements (Kyoto Protocol and EC Directive 2001/77/EC) to limit greenhouse gas emissions have to be limited to 13% above the 1990 level by 2008-2012.

This growth in the use of renewable energy to generate electricity has been encouraged by Government policies. The main instrument of encouragement has been the Sustainable Energy Ireland (SEI) under the Economic and Social Infrastructure Operational Programme (ESIOP) of the National Development Plant (NDP). Of the €185M public funding, €16.5M is designated to renewable energy (RE) in Ireland. The Government announced a possible target of 25% of electricity generated should be from renewable sources by 2010, subject to the cost to the consumers being acceptable.

The Green paper on Sustainable Energies set the following goals for Ireland RE programme. [4]

1. Total Primary Energy Requirement (TPER) to be increased from RE sources from 2% to 3.75%.
2. Increase electricity generated from RE sources from 6.3% (2000) to 12.39% by 2005.

The EC Directive 2001/77/EC has set the target for Ireland to increase the proportion of its electricity from renewable energy sources produce to 13.2% by 2010.

6.5.6 Thermoelectric Generation- Meteorology and Climate

The TE Collar does not release waste energy into the environment, but rather it utilises the climate to create a temperature gradient in relation to the body temperature. Therefore, the climate and weather have a vital role to play in the electrical generation impact in the form of temperature difference and cooldown via airflow.

Climate is highly influenced by its latitude proximity to the equator, the sun, the affect of forests and that of mountain ranges. These affect regions in terms of rain, wind and seasonal temperatures. Seasonal variation in the climate is represented by dry periods and rainy periods during the months of winter and summer depending on the region and location. During seasonal change, wind directions and their average velocity play a vital part of cooling down of the TE Collar heatsinks.

The TE Collar does not affect the climate or weather or emit heat, gas, particulate or waste in any form, chemical or biological to pollute the atmosphere. It is therefore considered as a 'clean' source of energy that does not contribute to global warming or temperature changes. In return, the climate influences the TE Collar in terms of energy output but does not cause interruptions due to weather or other disturbances to the electricity supply. Therefore, the security and availability of supply is certain.

6.5.7 Thermoelectric Generation- Geology Impact

Thermoelectric generation would impact in geothermal energy usage, which fall outside the scope of this Thesis. To utilize and ensure geothermal energy is used correctly, the bedrock or geothermal plates, which form part of the continental, should be stable and immune to the effects of seismic movements. Thermoelectric modules use no moving parts and cannot cause possible vibrations to the geo-environment. Therefore, the impact to the geology would be nominal if this application utilisation is considered.

6.5.8 Thermoelectric Generation- Body Energy Impact

Thermoelectric TE modules utilize the human body as the primary energy source in the form of waste generated by the body. Although this generated heat is low grade (see Chapter 5), the waste energy is free energy to be utilized in different formats. In this generation application, the delivered energy is relative constant in relation to the energy source. However, the useful energy changes with the environment conditions and the 'state of activity' of the body.

This 'free' waste energy is readily available. It is part of natural life process with a possible average lifetime >60 years of every human being. It is very reliable in comparison to other energy sources and it can be used globally. Its useful energy and low efficiency (2-5%) has already been discussed in great length in previous chapters.

6.5.9 Thermoelectric Generation- Transport

Unfortunately, thermoelectric generation can at this stage not impact on transportation except on small energy saving devices. With increased research, electric cars in the same format as solar powered driven cars will be widely available or as part of a hybrid system.

The definite advantage however lies in the transport associated with fuel (import of fossil fuels). Transportation would not be required as the renewable energy is widely available and an accessible energy source. Thermoelectric energy reduces the dependency and the transport cost of fuel over vast distances. It also reduces the vulnerability to disruptions of energy supply.

6.5.10 Thermoelectric Generation- Social-Economic Impact

In many countries today, fossil fuels need to be imported to provide electricity, heating and transportation. These imports are usually from countries rich in reserves. Due to concentrated reserves in certain countries, political and economic tension has developed. The cost of importing fossil fuels can add up to a considerable amount of any country's expenditure. The purchase of fossil fuels means that the local economy is affected by changes in the foreign and international market. In addition, electricity generation plants are usually centralised which creates vulnerability for strategic reasons and natural disasters.

Renewable energy resources are utilised locally using natural resources. This means that the collateral spent on energy in the country can be channelled into creating more jobs and stimulating local economic growth. The jobs evolving out of renewable energy plants in return create additional income and revenue. The economic advantages of renewable energy also extend beyond the local economy to the international market in terms of exporting technology or excess electricity.

6.5.11 Thermoelectric Generation- Noise Levels Impact

The TE Collar in itself does not generate any noise or utilize moving parts. The noise impact will be mainly from manufacturing the TE Collar, as noise levels at the manufacturing site will increase because of equipment use and related machinery. Manufacturing related activities will generate noise emissions of no more than 90 dB(A) measured at a distance of 5 meters from the source.

Most manufacturing plants incorporate fully automated facilities, implying that the employers would not be exposed to harmful noise levels apart from regulated scheduled maintenance.

6.5.12 Thermoelectric Generation- Health and Safety Impact

The health problems are primarily associated with the industrial part of the manufacture; in particular, the thermal conductive adhesive used for combine the heat/cold sinks to the TE Modules. Fully automated facilities reduce the risk of exposure in control-room environments so that the risk of exposure would be from accidents. The risk associated to exposure and accidents would depend on the nature and production techniques used by the manufactures. The impacts on the occupational health and safety are typical of a low to medium scale manufacturing industry. No adverse health conditions or critical worker safety conditions are foreseen during the construction of the TE Collar.

The nature of health and safety concerns in the manufacturing and operation phase vary from outdoor to indoor occupational hazards, such as appropriate lighting and ventilation, noise levels, fire prevention, among others. Although the likelihood of an accident is minimal, risk assessment and contingency planning will be considered along the TE Collar development.

6.5.13 Thermoelectric Generation- Waste and Contamination

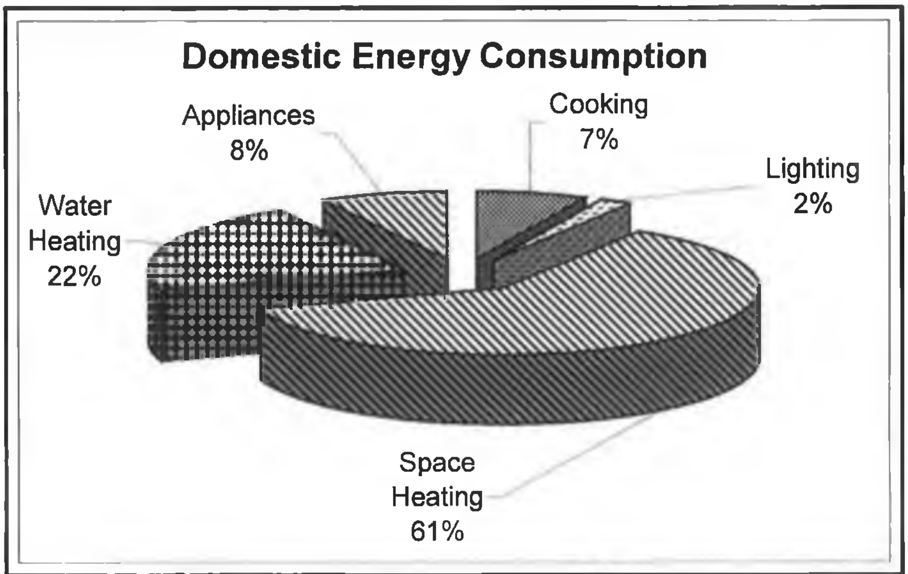
TE modules do not need to be replaced continually like batteries and may function for decades, thus, they reduce waste. In their best application, TE modules utilise waste heat for electrogeneration and reduce natural dependencies on fuels or minimise such as a secondary generation device in heat pump applications. In conventional generation, the production of solid waste, as well as Class I waste (oil and oily sludge from effluent treatment systems and chemical product packaging) produce solid waste materials classified as hazardous that contaminate the environment. Energy generated from fossil fuels is also a primary source of air, water, and soil pollution. Pollutants, such as carbon monoxide, sulphur dioxide, nitrogen dioxide, particulate matter, lead and other waste take a dramatic toll on our environment. Other impacts of include acid rains, oil pollution and radioactive waste.

Unlike most conventional generation plants, renewable energy does not require water as a coolant or energy transfer medium. The requirement for cooling water systems, pump stations for circulating water, the dosage of chemical products used in treatment of water and cooling towers is not required. Each of these impact on the water or air quality, which may contaminate the fauna and flora. Chemical and treatment tanks used by conventional generation plants may leak due to construction defects or poor maintenance and contaminate the soil and underground water. Normally, renewable energy generators do not effect or degrade natural forest, water or habitats.

6.5.14 Thermoelectric Generation- Domestic Impact

Globally, energy consumption in the domestic sector is 29% or 115EJ. Domestic sector energy use is affected by the size of the population, the number of households, local building regulations and by the housing layout in terms of age, building type, ownership, and location. Recent years, the tendency for smaller households has increased. This results in higher per capita energy consumption. Building and Governmental regulations have also been tightened to ensure that homes are becoming more energy efficient in terms of energy consumption, house construction and awareness of energy saving by improving households understanding of energy use.

From Table 6.1, the projected rate of energy usage in the domestic sector is: low heating/ cooling (65W/cap), space and warm water heating (152W/cap) and appliances (240W/cap). Although the household growth increased by only 10%, annually, total household energy consumption has increased by 30%. This increase in demand is mainly in comfort environment provision and for powering appliances.



Graph 6.3 Domestic Energy Consumption [6]

Space heating has the highest level of energy consumption (see Graph 6.3). Great effort has been made to reduce this figure by changing insulation to buildings and homes. With increase in technology, computer and home entertainment will increase the energy consumption in households considerably. Currently only 8% of the energy consumption is used on appliances and set to rise to 32% of the total household usage in the near future. This will open the market in terms of energy saving in domestic energy consumption considerably. It is in this sector that thermoelectric and other renewable energy sources would serve best.

6.6 Conclusion

Why use thermoelectric energy? The answer lies with renewable energy and today's usage of non-renewable energy sources. It is evident that the world is in an energy crisis. Not only is the amount of energy reducing (Second Law of Thermodynamics; Entropy) but also the amount of usage, consumption and requirement is increasing globally. The estimate cut-off is between 2020 and 2050 when the world will have exhausted all its natural energy resources.

Wars have already been fought for energy in e.g. Iraq, Afghanistan, Angola, Nigeria, Kazakhstan and many oil producing countries including some of these are political undermined to ease the exploitation of their natural resources. The process has been set in motion as developed countries use military, economic and political manoeuvres to gain, dominate and govern these precious resources. In the aftermath of electrical power failures in developed countries because of overloaded gridlines (USA 2003, Italy 2003), countries have become aware of energy shortages and the looming crisis. The fluctuation in electricity demand is of great concern as demand and supply cannot always be met in peak hours.

Alternative or intermediated energy sources are required. In comparison to other energy sources, thermoelectrics are minute in usage and generation, but in the author's opinion vital. Energy impacts our entire humane continuation, and therefore, independent energy generation is required, not only due to the energy crises but for the preservation of the independence and individualism of each person.

Chapter 7- Thermoelectric Generation Feasibility Assessment

7.1 Project Summary

With the increase in technology especially in the telecommunication and computerised sector in the past 20 years, alternative power generation for handheld and other DC voltage applications have attracted wide attention. The current market sector is estimated at €5 billion annually. Among these rank renewable energy power sources and devices like thermoelectricity. Thermoelectric material application is particular to solid-state refrigeration and power generation.

With thermoelectric materials, a temperature gradient is generated when an electromotive force is applied to these materials and an emf produced when the materials are placed in a temperature gradient. It is with this applied temperature gradient that power generation from the human body is sought. In Chapter 2, current applications for TE materials and thermoelectric generation based on bismuth telluride alloys are explored in more detail. Although widespread applications are limited because of low efficiency, recent research suggested that the efficiencies of these materials is improved by quantum confinement, for example the fabrication in the form of one-dimensional (1-D) nanowires. Other research focuses on microelement manufacture with thin-film layer deposits laser-machined into pixels to form thermocouple pairs.

The main objective of this thesis is to synthesize a device to produce electricity for hand held devices via current thermoelectric materials available on the market. The first part of this thesis involves determining optimal conditions of thermoelectric materials (Chapters 1, 3 & 4). The second part of this thesis focus on the human body as an energy source (Chapter 5). The third part of this thesis focus on renewable energy, its market sector and generation impact (Chapter 6). This fourth part focus on the feasibility in using this technology as a power source in generating electricity for hand held devices (Chapter 7).

7.2 Project Description

Joining two thermoelectric materials with opposite charge carriers and applying heat to one side produces thermoelectric power generation. The purpose of this thesis chapter is to research the feasibility of using Peltier modules to generate electricity via body heat.

Projected Outcomes:

- Optimized methodology for the manufacture or design of the TE Collar;
- Improve the layout of the TE Collar to increase efficiency;
- Assessment of the thermoelectric properties used in the fabricated TE Collar;
- Assessment of alternative thermoelectric materials; and
- Assessment of the DC-DC Converter and alternative output voltages.

Anticipated Benefits:

Advantages of thermoelectric power generation include:

- No emissions, no moving parts and quiet operation;
- Can operate from waste heat;
- Proven technology with known characteristics and outcome;
- Continuous power anywhere;

- Long life expectancy;
- Lightweight and self containing power source;
- Can operate under diverse conditions; and
- Can adjust the output voltage according to requirements.

7.3 Thermoelectric Generation Feasibility Assessment

7.3.1 Introduction

Determining the feasibility of the TE Collar and thermoelectric generation involves investigating whether this idea is likely to succeed. The fundamental or research question is: *Is it therefore feasible to study the applications for waste heat electrogeneration utilising thermopile application methods?* If this process determines whether to proceed with, alter, or drop a plan of action, the question will be answered. There is no right or wrong answer in the feasibility study as it only emphasis the evidence on the success or failure of this idea.

7.3.2 Assessment

Aspect A. Feasibility Assessment

Technical Feasibility - Does the expertise and technology exists to implement the concept into the system design for integration and into the market place? Already during the past years, with the increase in device applications, the technology and research into improved materials add to the feasibility in using thermoelectrics. It is now feasible in using industrial modules in producing electricity.

Economic Feasibility - Can the prototype model system be built within budget, and how much would the finale product cost? It is estimated that the potential product cost will be approximate €255-00/unit. This include for the modules, the DC-DC Converter, connections, heat sinks and bonding materials. However, this does not account for the reductions in cost via mass production, reducing the specification or alteration of the final product assembly. Operating costs and variable costs of the manufacturing of this item are not included at this stage. Since there is no annual operating cost, maintenance or replacements required, the yearly cost is not calculated.

Schedule Feasibility - How much time and input is required to contribute to complete the finale project? How long will it take to bring this concept to the customer? Obviously, market refinement is required as well as further product development. However, the basic concepts and layout as well as the materials are selected, which in turn will reduce the time input considerable. The concept time will be determined by time of approval on the finale product

Performance Feasibility - How well will the proposed prototype model and the concept actually perform to its function? Will it meet the customer's needs assessment? What is the overall ability of the concept to meet all regulatory requirements? How does the concept meet the customer's requests that are not essential to the underlying goals and functionality?

What industries are being targeted?

The major industry being targeted is the communications market. This market includes the military and industrial market as well as consumers. An adaptive market in combination with the above is the sustainable energy sector.

What is the size of the industry?
The communications market sector is estimated at €5 billion annually and increasing due to innovations and increases of technology.

What is the growth rate of the industry?
This is a growing market and has increase in size since the nineties due to technological advancements In the renewable energy sector there is a growth from 1996-2000 of 6.95% and an estimated growth of 7.21% over the next five years at [4].

Who are the major players in this industry?
The major players are Sony, Motorola, National Panasonic, Nokia, Siemens, Philips and any manufacture in the renewable energy sector.

What are the strength and weaknesses of the industry?
Strength
Continuous development, refinement and new concepts are required to keep sales up

Weakness
The Product may have short life Cycle, is expensive and may appeal only to selective market

What are the opportunities and threats in the industry?
Opportunities:
- Legislation require sustainable energy sources and environmental impact and
- No competition.

Threats:
- Alternative and better products may become available to the market;
- Energy market changes constantly and adapting to new discoveries and technology;
- New market involves risk with extensive market research required;
- Customers may be resistant to the innovation; and
- Possible health and safety implications.

What are the current trends in the industry?
The newer update, the better, the quicker and more functional applications. Desireble to have and cableless appliances.

7.4 Pros and Cons in Thermoelectric Generation Usage
In any application, there are advantages and disadvantages in the use of that system or technology. The same applied to thermoelectric generation. The following need to be considered in the usage of this application:

7.4.1 Pros:
- Low cost of the units in manufacturing and supply;
- No moving parts, less equipment is used in construction, substantially less maintenance required and unlikely to be broken;
- Can be used in a wide temperature range and applications;

- Generates a reasonably short response time;
- A repeatability and accuracy in testing and usage exists;
- TE devices are capable of exceeding 100,000 hours of steady state operation;
- TE devices contain no other materials that may require periodic replenishment or refill;
- Accurate temperature control is maintain using TE devices via the appropriate support electronic circuitry;
- TE devices can function and operate in harsh and extreme environments;
- TE devices are not position-dependent. It may be used on other areas on the body or other equipment generating heat;
- The direction of voltage generation in a TE system is fully reversible. Changing the heat pump direction will change the polarity of the DC power generated;
- The size and weight of TE devices ensure position and usage in almost every situation;
- TE devices are capable of high mechanical stress and wear; and
- TE Devices is environmental friendly therefore acceptable as an generation device without legislation or legal implications

7.4.2 Cons:

- Sensitivity is low, usually 50 µV/°C or less. Its low voltage output may be masked by noise. This problem can be improved, but not eliminated, by better signal filtering, shielding, and analog-to-digital (A/V) conversion or the use of DC-DC Converters;
- Accuracy, usually no better than 0.5°C and may not be high enough for some applications like measuring purposes;
- Temperature conditions affect the performance of TE device directly. (Refer to Chapter 6, Item 6.7);
- Non-linearity could be bothersome. However, detail calibration curves for each wire material can usually be obtained from vendors; and
- Low efficiencies do not make them popular in certain applications.

7.4.3 Durability of the TE Collar

Commercial, industrial and military applications look for durability as well as consistency in electrical generation devices. Although the TEMs used in this thesis are potted and therefore water-resistant, usage of these module under all kinds of weather and conditions as well as handling, duration and storage should be attentive.

Tough handling, temperature extremes as well several drop tests to the TE Collar still ensure electrical generation due to the compatibility of the materials and robust construction.

7.5 Compatibility of Handheld Devices

7.5.1 Batteries and Rechargeable Batteries

For handheld devices, the range of input voltage allows using alkaline, nickel cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), or rechargeable alkaline batteries. When Ni-Cd batteries are charged, nickel hydride $Ni(OH)_3$ an active material appears on the positive plates and on the negative pure cadmium. In the discharge condition, the $Ni(OH)_3$ is converted to a lower hydroxide $Ni(OH)_2$ and the cadmium to cadmium hydroxide $Cd(OH)_2$. For Nickel-Metal Hydride batteries, the reactions are similar, except metal particles replace the cadmium. The chemical reaction in a nickel-cadmium cell can be summarized as:

Positive Plate	*Negative Plate*		*Positive Plate*	*Negative Plate*
$2Ni(OH)_3$	Cd	Discharge→ ← Charge	$2Ni(OH)_2$	$Cd(OH)_2$

The size of the battery cell is not the only factor that affects available current. The length of time the device run before the battery discharge and need to be replaced or recharged is affected as well. Faraday's laws implies best to the limitations of batteries:

$$m = zIt \tag{7.1}$$

where 'm' is expressed as the mass, 'z' the electrochemical weight equivalent of the element and 't' the time in seconds. The amount of elemental substances liberated by electricity are proportional the chemical equivalent weights or the atomic weight per valence electron.

Not only does the TE Collar compete with batteries as a power source, but also the ultimate aim is to completely replace batteries as a power source or reduce the dependency of battery usage. This may be accomplish through utilising batteries as a storage or backup to the primary supply (the TE Collar). See below Table 7.1 for the specification of the NiMH rechargeable battery:

NiMH Battery NB-1AH	
Type	Rechargeable Nickel Metal Hydride Battery
Nominal Voltage	1.2V DC
Typical Capacity	1600mAh
Cycle Life	Approx. 300 times
Operating Temperature	0-35°C
Dimensions	Diameter: 14,4mm, Length 50mm
Weight	Approx. 27g

Table 7.1 NiMH Battery NB-1AH Specifications

Drawbacks of rechargeable batteries

- The batteries self discharge (lose their charge) when not in use;
- The batteries have to recharge and discharge a couple of times after inactivity;
- Battery life is approximate 300times charge and discharge;
- The batteries become warm (increase in temperature) when charging;
- Dirt build-up forms on battery poles and need to be cleaned often;
- Noise appear on electrical appliances when charging;
- Direct sunlight or heat sources (less than 35˚C) affects charging;
- Time delay (up to 220minutes) in the charging cycle of batteries depending on type, initial charge status and ambient conditions;
- Dedicated electrical commercial outlet sockets required for charger;
- Only certain types of batteries on certain chargers may be used;
- Batteries cannot be inserted with reverse terminals;
- Batteries are damaged when in contact or immersed in water;

- Batteries may leak, overheat and explode;
- Leaving batteries for prolonged times may cause damage in equipment;
- Batteries are damaged with strong shocks;
- Batteries may be overcharged;
- Batteries may cause personal injury;
- Batteries performance deteriorates at low temperatures;
- Repeatedly recharging may lose battery capacity;
- New and used batteries cannot be used at the same time;
- Batteries of the same charge, type and purchase date should be charge at the same time;
- Batteries give a short low-battery warning time;
- Batteries contain toxic substances; and
- The number ampere-hours obtainable are affected by the discharge rate.

In a cost comparison between the use of thermoelectric generation, disposal and rechargeable batteries, the following:

Item	Description	Disposable Batteries	Rechargeable Batteries	Thermoelectric Generation
1.	Life Expectancy: hours	4	4 x 300 charges = 1200	100000
2.	Cost in use or Construction	€ 6.00	€ 30.00	€ 255.00
3.	Cost per Hour (€ / hour)	1.5	0.03	0.0026
4.	Comparison: Batteries/Rechargeable TEG/Batteries TEG/Rechargeable	 0.0167 0.007 --	 60 --- 0.102	 --- 588 9.8

Table 7.2 Cost comparisons between Disposal, Rechargeable Batteries and TE Generation

A cost comparison was done in the continuous usage of power to devices according to the cost of each power source. It is clear from Table 7.2 that the usage of thermoelectric power is 9.8 times cheaper than the use of rechargeable batteries and almost 600 times in comparison with normal alkaline batteries. It is also clear the advantages in the use of thermoelectric power above the use of rechargeable batteries and that the only uncertainty is the heat source required and the efficiency by the TE application.

7.5.2 Hand Held Devices Electrical Requirements

Most electronic devices utilise DC voltage. Table 7.3 indicate the comparison between the popular hand held devices and electrical power requirements. It is apparent that most handheld devices operate at a low voltage and in the same region the application of the TE Collar is proposed. Therefore the benefits to utilise the TE Collar as a substitute to batteries or other energy proposals is evident, recommendable and feasible.

	Power Consumption			Battery	Battery Duration	Battery Type
Device	Voltage	Ampere	Wattage			
GPS (Magellan SporTrak)	---	---	---	2xAA	14hrs	Alkaline
VHF Radio's (Icom IC-1MV)	7.4VDC	TX1.5A/ RX200mA	5W 1W	7.4V Pack	10hrs	Lithium Ion Rechargeable
Police & Fireman Scanners (Uniden BC245XLT)	12VDC	---	---	4x1.5AA	---	Ni-MH Rechargeable
2 Way Radio's (Motorola CP150)	7.2VDC	---	2W	7.2V	9hrs 17hrs	Ni-MH Lithium Ion
Palm Tops (Sony PEG-TJ37)	5.2VDC	---	---	5.2V	300min	Lithium Ion
Digital Camera's (Canon A70)	4.3VDC	1.5A	---	4x1.5AA	280min	Ni-MH Rechargeable
Computer Laptop	14VDC	4A	60W	1-off	240min	Lithium Ion Rechargeable
Camcorders (Sony DRC-DVD100)	7.2VDC	---	5.5W	7.2V	---	Lithium Ion Rechargeable
MP3/CD Player Walkman (Sony D-NE1 ATRAC3)	4.5VDC	---	---	2x1.5AA	90hrs	Ni-MH Rechargeable
Radio Walkman (Sony SrF-M37V)	1.5VDC	---	---	1x1.5AAA	50hrs	Alkaline
Cassette Walkman (Sony S2 Sport) (Matsui BB4 MKII)	1.5VDC 4.5VDC	--- 200mA	--- ---	1x1.5AA 2x1.5AA	35hrs	Alkaline Alkaline
Mobile Phones (Nokia 3310)	3.6VDC	---	---	3,6V	---	Ni-MH Rechargeable
Video Walkman (Sony GV-D200)	7.2VDC	---	5.5W	7.2V	---	Lithium Ion Rechargeable
Hand held meters (HP48G Calculator)	---	---	---	3x1.5AAA	---	Alkaline
Digital Multi-Meter (Circuit-Test DMR-500)	9VDC	3.5mA	30mW	4x1.5AA	60hrs	Alkaline
Note: Actual battery life varies according to temperature and conditions of device use.						

Table 7.3 Hand Held devices electrical power specification and comparison [3]

7.6 Thermoelectric Feasibility Assessment Conclusion

Increasing requirements in electronic hand held applications are: (i) the battery operating duration or energy consumption rate, (ii) reliability in energy supply, (iii) the availability of charging outlets and (iv) frustration of charging times. The drawback in primary or secondary cells is it can transform only chemical energy in electrical energy and that the cell replenished by renewal of the active materials or recharging a certain number of times before replacement.

With thermoelectric energy, power is there where and when you want it and it is virtually limitless. This item is life sustainable in terms of electricity in remote and emergency situations for electrical appliances.

Chapter 8- Experimental Values and Derivations

8.1 Introduction

The TE Collar is designed for the utilization of body skin temperature and to determine the maximum power or voltage generated by this system. Several experimental set-up conditions were simulated to produce combinations on airspeed, activity and temperature conditions. This data was subsequently used to define the optimal performance of the TE Collar under these conditions and to determine the feasibility of such a system

The experiments consisted of the TE Collar assembly, composed of individual thermoelectric modules (TEMs), bounded to heatsinks in such a manner to be used around a person's neck or upper leg. The combination of TEMs with the heatsinks forms a modular integral assembly unit named by the author as a TE Collar. In order to generate higher and faster stability and electricity generation, a heatsink to the skin was excluded as shown in Figure 8.2. Consequently, the results were influenced to the advantage of the experimental values, data, temperature and the practical construction of the TE Collar and its characteristics.

The TE Collar was used in several conditions. All the initial temperatures was measured via a digital multi-meter (type Circuit-test DMR-5200) with RS-232C Interface to a computer. A 'K' type thermocouple temperature probe with a temperature range of –20 °C to 1200°C was used.

All the digital multi-meter signals were transferred to a PC computer via a RS-232C interface and the results logged to a spreadsheet program.

8.2 Voltage Generation Experiments

Experiment Method #1:

The first test was designed to determine a single TEM performance under ambient temperature and body temperature. The TEM was positioned directly on the skin surface on the hand palmtop with the heating side to the skin and the cold side exposed to the environment (See Figure 5.1).

The test was conducted for a body skin temperature of 29°C (measured) without any heat and cold sinks attached. The room temperature (ambient temperature) was measured at 22°C without noticeable air movement (less than 0.5m/s according to the Beaufort Scale Table 11.3). The following conditions applied:

Ambient Temperature (T_2)	22°C (measured)
Skin Body Temperature (T_1)	29°C (measured)
Duration of test	180 seconds
Materials used	Peltier TM Models
Manufacture	TE Technology
Type	TM-HP-127-1.0-1.3-71 (Unpotted)
Dimensions (W x L x D)	30mm x 30mm x 3mm
Amount	1
Position used	Hand, palmtop
Heatsink	Not included
Measured	Voltage and Ampere
Activity	Rest, no body movement

Results of Experiment #1:
The TM generated a voltage from 0mV to 80mV within 5s. When the maximum generated voltage of 80mV was reach, a voltage drop occurred. The voltage dropped at a constant rate exponentially to 30mV in 120s or 2minutes and then stabilised at 31mV. See the attached Graph 6.1 below.

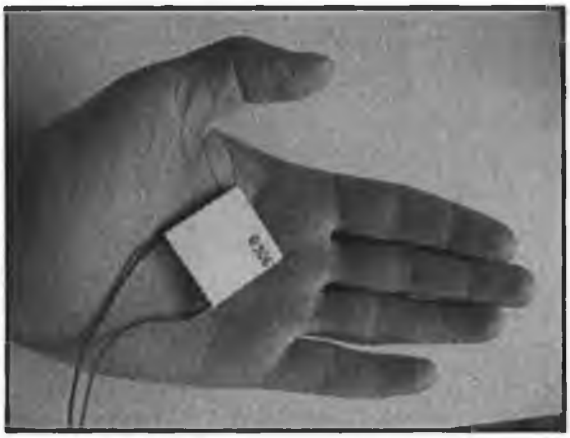
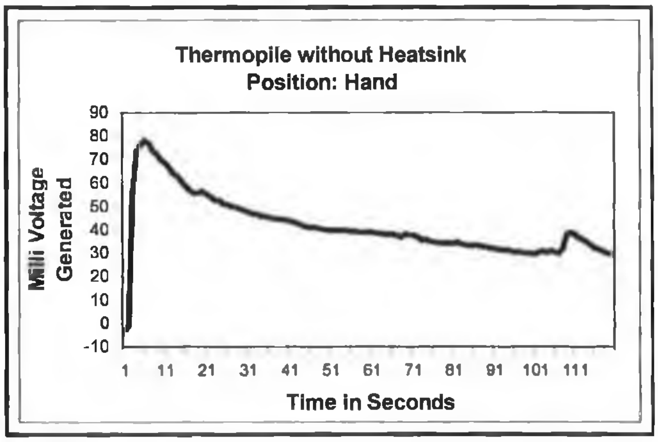


Figure 8.1 Photograph Author with Single TM on palmtop of hand



Graph 8.1 Voltage Generated by Single TM

The following possible explanations might be considered for the behaviour of the TM:

a. The heat flow bridge passes heat from the hot side to the cold side, minimising the efficiencies.
b. Another consideration is the heating up of air around the TM causing the behaviour of the voltage generated due to the heat transfer rate and ΔT been reduced.

The test indicated that a skin and TE module surface area of 0.0009m^2 was able to deliver an average voltage of 41.5mV in ambient conditions. With this result, a skin area of 1m^2 will be able to generate 46.11V in similar conditions. The aim of this thesis is to generate 1.5V and therefore require an area of about 0.0144 m^2 with current conditions and set-up.

Experiment Method #2:
The next test was designed to repeat Experiment Method #1 with complete TE Collar; heatsinks excluded, to determine the total expected amount of voltage being generated under ambient temperature, body skin temperature under controlled conditions. Refer to Figure 8.2 below. The following conditions applied:

Ambient Temperature (T_2)	18°C (measured)
Skin Body Temperature (T_1)	33°C (measured)
Duration of test	360 seconds
Materials used	Peltier TM Models
Manufacture	TE Technology
Type	TM-TE-63-1.0-2.5P (Potted)
Dimensions (W x L x D)	30mm x 15mm x 3mm
Amount	17 in series connection
Position used	Neck
Heatsink	Not included

Measured	Voltage and Ampere
Activity	Rest, no body movement

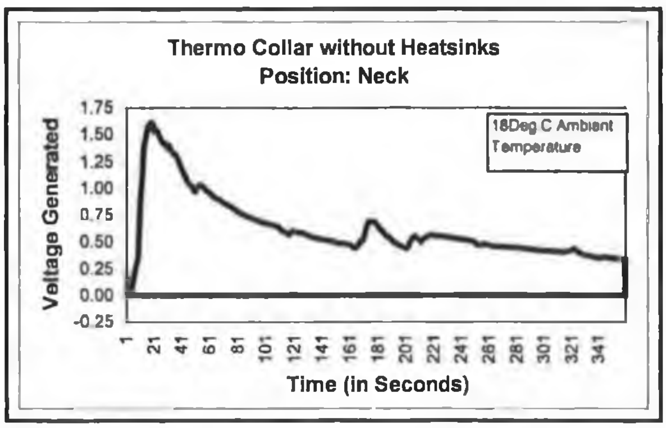
The TE Collar modules were positioned directly on the skin surface. This was to ensure direct transfer of heat through the thermoelectric modules and the maximum efficiency without the coldsinks. The TE Collar was positioned directly to the neck position and real time experiments carried out.

Results of Experiment #2:

After repeating the experiment with the complete Thermoelectric Collar, it was found that the TE modules conducted the heat away from the skin area at a higher rate where the TEM was positioned. The skin area rapidly decline in surface temperature and thus reduces the heat available to the TEM. This resulted in a drop of voltage generated. This may be best explained with the amount of heat conducted away from the skin to the TEM is much greater than the heat and blood flow to that area. Also the amount of time for the skin area to recuperate or to adjust to this heat conduction draw-off was not enough or the reaction time too slow to adjust and compensate.

So, the initial draw-off rate is much greater than the heat provided by the skin area in contact. Therefore by closing of blood vessels and the reduction of blood flow to the skin area in contact with the TEMs is due to the sudden drop of temperature created by the TE modules and thus reduces the amount of heat energy available to that particular skin area.

Figure 8.2 Photograph of the TE Collar without heatsinks



Graph 8.2 Voltage Generated by Thermoelectric Collar- Neck

Another consideration is the heat transfer across the TEM. Initially the TEM is at room temperature. With contact to the heating source, the skin, the sudden increase and temperature difference cause the voltage to rise to a maximum in a short space of time. This causes the voltage generated to peak. As soon as the TEM module warms up to the skin temperature, less voltage is generated due to the draw-off rate, lack of cooling, as well as the lower heat transfer rate. This explains the exponential drop in generated emf until the voltage generated equals the heat transfer rate to the ambient environment.

The effect is also due to the lack of a heatsinks to conduct, 'pump' or direct the heat away from the TEMs. Thus, the result is the heat is 'trapped' inside the TE modules and reduces their effectiveness. This causes the outer aluminium band to heat up to the same temperature as the skin temperature, minus the temperature radiated away from the band.

Note: Not all the TEMs were in full contact with the skin at the same time due to the stiffness of the aluminum band. Therefore the complete effectiveness of the TE Collar could not be reached. To mitigate this problem, the TE Collar needs to be made more flexible and the Aluminium band replaced with of nylon straps. This is addressed in more detail in Chapter 9.

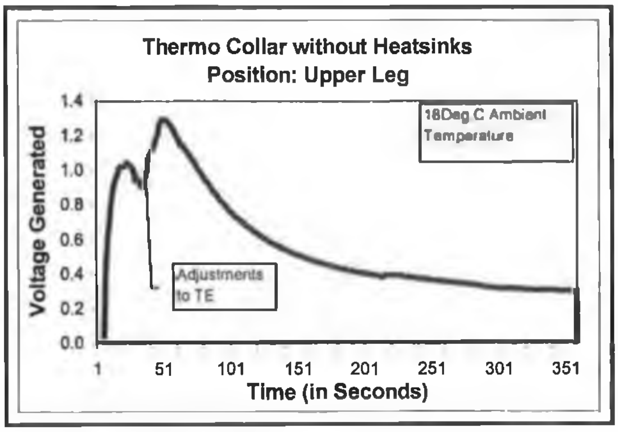
Experiment Method #3:

This is a repeat of Experiment #2 with the complete TE Collar, Heatsinks excluded. The third test was designed to examine a different positioning of the TE Collar. This was to determine if other positions on the body might be a more suitable or preferred and allow more diversity in the positioning and usage of the TE Collar. The following conditions applied:

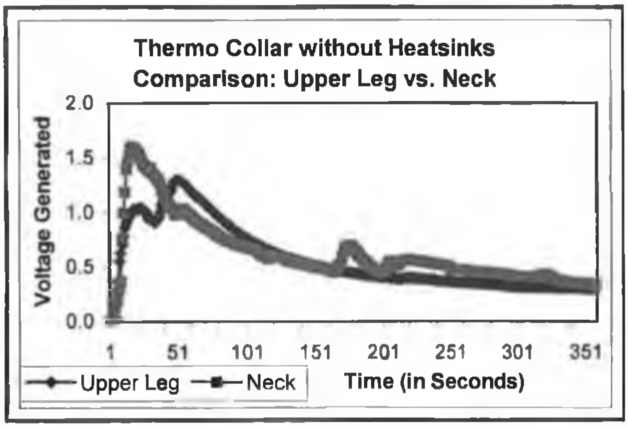
Ambient Temperature (T_2)	18°C (measured)
Skin Body Temperature (T_1)	28°C (measured)
Duration of test	360 seconds
Materials used	Peltier TM Models
Manufacture	TE Technology
Type	TM-TE-63-1.0-2.5P (Potted)
Dimensions (W x L x D)	30mm x 15mm x 3mm
Amount	17 in series connection
Position used	Upper leg
Heatsink	Not included
Measured	Voltage and Ampere
Activity	Rest, no body movement

Results of Experiment #3:

The test was conducted to the upper leg skin temperature of 27°C (estimated) without any heat and cold sinks attached. The room temperature (ambient temperature) was measured at 18°C without noticeable air movement. The TE Collar aluminium band temperature was measure after the experiment and found to be less than 1°C difference between the upper leg skin temperature and the band.



Graph 8.3 Voltage Generated by Thermoelectric Collar- Upper Leg



Graph 8.4 Evaluation of voltage generated between Neck and Upper Leg position

Again, the graph and measurements indicate the loss of generated electricity due to the saturation and heat transfer rate to the aluminium band. The requirement for heatsinks is evident to produce a successful model for the use of body thermoelectric generation.

The TE Collar generated a maximum voltage of 1.292V, and then dropped exponentially to the lowest value of 0.299V. The maximum voltage generated is 0.308V or 19.25% less than at the neck position. The lowest or stable voltage is also 0.299V or 10.7% less than at the neck position. See Table 8.1 and Graph 6.4, for the performance evaluation between the neck and upper leg positioning of the TE Collar:

Item	Description	TE Collar	
		Neck Position	**Upper Leg Position**
1.	Maximum Voltage Generated	1.6 V	1.292 V
2.	Lowest Voltage Generated	0.335 V	0.229 V
3.	Position Temperature (T_h)	33°C	27°C
4.	Ambient Temperature (T_a)	18°C	18°C
5.	Temperature Difference (ΔT)	15°C	9°C
6.	Average Voltage	0.62 V_{avg}	0.56 V_{avg}

Table 8.1 Comparison on performance between the neck and upper leg position

Although the maximum voltage generated is less than that of the neck position, this experiment clearly shows other positions on the body are also feasible in using TEM for the usage of thermoelectric generation.

From Graph 6.4, the comparison between the neck and upper leg positions shows that the two positions perform identically at similar conditions. Therefore preference engineering to the positioning of the TE Collar applies. Although the neck position generated more voltage than the upper leg position (due to a higher body temperature), the neck is in most cases more exposed than the upper leg to the environment. With the upper leg mussel contraction in walking or running, as well as the expansion of blood vessels (and muscles) and with the increase in blood flow when exercising, chafing will occur in normal day-to-day applications. Chafing might also occur from the TE Collar positioned on the upper leg to the other leg. Also the limbs generate less heat than the neck area. Therefore, it would be preferable to position the TE Collar at the neck as per original design and intention.

It is however interesting to note that the upper leg provided full contact to the TEMs of the TE Collar due to increased circumference or bulk. This is reflected in the measurements taken to be almost the same as at the neck position, even with the temperature difference (compare ΔT=9°C at upper leg with ΔT=15°C at neck).

<u>Experiment Method #4:</u>
This is a repeat of Experiment 2 with complete TE Collar, heatsinks included. This test is designed to determine the performance of heatsinks added to the TE Collar and the total voltage generated under ambient temperature and body skin temperature at the neck position. The following conditions applied:

Ambient Temperature (T_2) 18°C (measured)
Skin Body Temperature (T_1) 33°C (measured)

Duration of test	360 seconds
Materials used	Peltier TM Models
Manufacture	TE Technology
Type	TM-TE-63-1.0-2.5P (Potted)
Dimensions (W x L x D)	30mm x 15mm x 3mm
Amount	17 in series connection
Position used	Neck
Heatsink	Included
Measured	Voltage and Ampere
Activity	Rest, no body movement

Results of Experiment #4:
The TE Collar with heatsinks added (refer to Figure 8.3), generated electricity at a maximum of 1.909V with the lowest end value of 0.382V (see Graph 8.5). The comparison between the usage to include a heatsink and without, indicated a 19.3% increase in electricity generated with the heatsink included. At the same time the lowest voltage generated was 14% higher than the TE Collar excluding heatsinks. The average voltage generated, V_{avg} was overall 15.8% higher with heatsinks included. See below Table 8.2 for the comparison of the application with or excluding the use of heatsinks to the TE Collar.

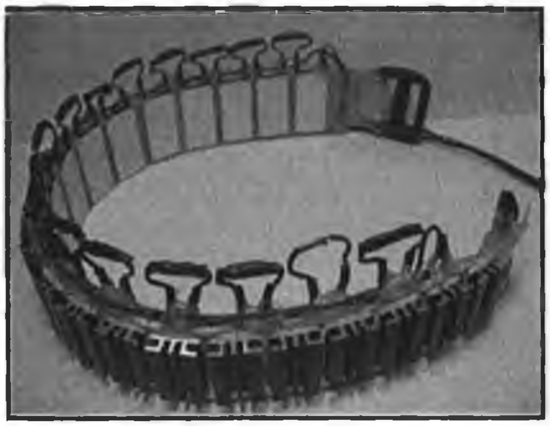
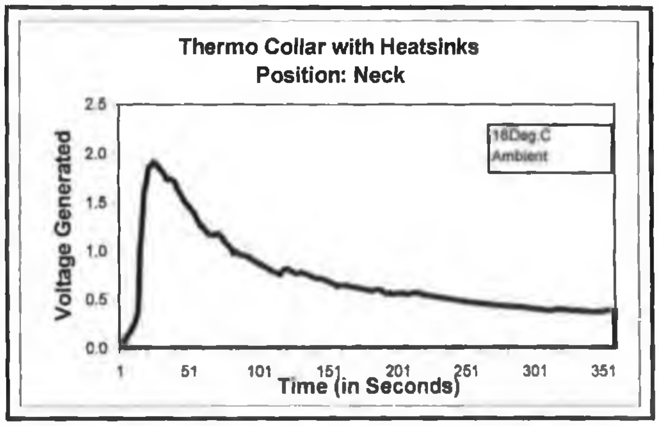


Figure 8.3 Photograph of the TE Collar with heatsinks



Graph 8.5 Voltage Generated by Thermo-electric Collar- Neck position

Item	Description	TE Collar	
		Neck Excluding Heatsinks	**Neck Including Heatsinks**
1.	Maximum Voltage Generated	1.6 V	1.909 V
2.	Lowest Voltage Generated	0.335 V	0.382 V
3.	Position Temperature (T_h)	33°C	33°C
4.	Ambient Temperature (T_a)	18°C	18°C
5.	Temperature Difference (ΔT)	15°C	15°C
6.	Average Voltage	0.62 V_{avg}	0.718 V_{avg}

Table 8.2 Comparison of performance on the TE Collar neck position (in- and excluding heatsinks)

The use of heatsinks increased the overall heat transfer from the source to the ambient environment. In addition, greater stability with higher voltages was generated.

Heatsinks ensure a more constant heat dissipation and therefore heat transfer across the thermoelectric module. The TE module heat pump capacity increased the overall efficiency of the application as a whole. The heatsink performance is dictated by the type of activity to ensure airflow around the sinks. This allows better heat dissipation away from the TE Collar and enhances the overall performance of heat transfer away from the heat source through the modules to the ambient environment.

Experiment Method #5:

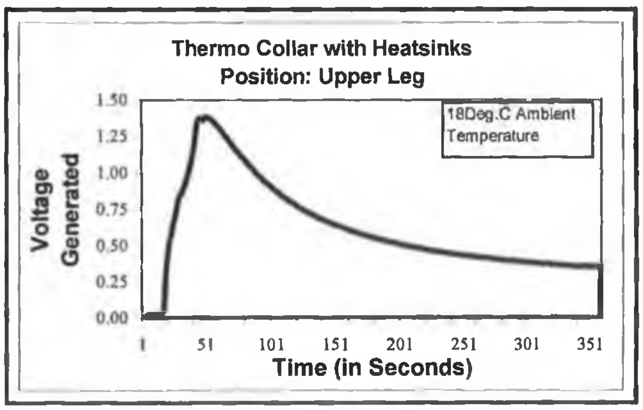
This is a repeat of Experiment 3 with the complete TE Collar, heatsinks included. This test is designed to determine the performance of heatsinks added to the TE Collar and the total voltage generated under ambient temperature and body skin temperature at the upper leg position. See Figure 6.4 below. The following conditions applied:

Ambient Temperature (T_2)	18°C (measured)
Skin Body Temperature (T_1)	33°C (measured)
Duration of test	360 seconds
Materials used	Peltier TM Models
Manufacture	TE Technology
Type	TM-TE-63-1.0-2.5P (Potted)
Dimensions (W x L x D)	30mm x 15mm x 3mm
Amount	17 in series connection
Position used	Upper leg
Heatsink	Included
Measured	Voltage and Ampere
Activity	Rest, no body movement

Results of Experiment #5:

The results of this experiment follows the same exponential decline in voltage generated over time as at the neck position and the excluding of the heatsinks. See Graph 8.6 below.

Figure 8.4 Photograph of the TE Collar positioned on upper leg



Graph 8.6 Voltage Generated by Thermoelectric Collar- Upper leg position

In the overall comparison (see Table 8.3 below), with the inclusion of heat sinks, a 6.5% increase in the maximum voltage is generated. The most noted difference is a 53.3% increase in the lowest voltage generated without heatsinks attached. The average voltage V_{avg}, also increase by 8.9%.

Item	Description	TE Collar	
		Upper Leg Excluding Heatsinks	Upper Leg Including Heatsinks
1.	Maximum Voltage Generated	1.292 V	1.376 V
2.	Lowest Voltage Generated	0.229 V	0.351 V
3.	Position Temperature (T_h)	27°C	27°C
4.	Ambient Temperature (T_a)	18°C	18°C
5.	Temperature Difference (ΔT)	9°C	9°C
6.	Average Voltage	0.56 V_{avg}	0.61 V_{avg}

Table 8.3 Comparison of performance on the TE Collar upper leg position (in- and excluding heatsinks)

Experiment outdoors

Experiment Method #6:

This experiment is designed to determine the TE Collar performance with normal day-to-day activity under ambient temperature and body temperature. The TE Collar was positioned directly on the skin surface of the neck with the heating side to the skin and the cold side exposed to the environment. Heatsinks were excluded. The following conditions applied:

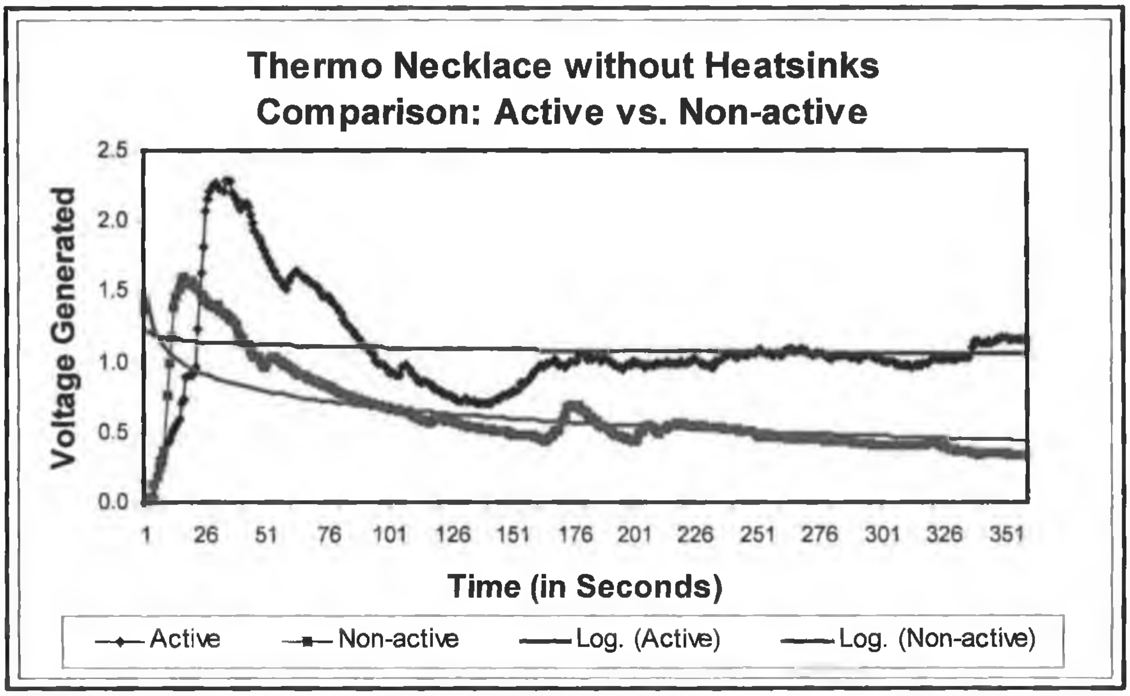
Ambient Temperature (T_2)	11˚C (measured)
Skin Body Temperature (T_1)	33˚C (measured)
Duration of test	900 seconds
Materials used	Peltier TM Models
Manufacture	TE Technology
Type	TM-TE-63-1.0-2.5P (Potted)
Dimensions (W x L x D)	30mm x 15mm x 3mm
Amount	17 in series connection
Position used	Neck
Heatsink	Excluded
Measured	Voltage and Ampere
Activity	Low activity- Walking

Results of Experiment #6:

In Chapter 5, Table 5.3, the associated energy cost for a low activity like walking equals to 586J/m^{2}hr. The maximum energy generated is 2.267V from the TE Collar during this experiment with the average voltage V_{avg} of 1.089V including the cool down period. Reasons for increase in voltage generated may be explained as followings:

1. Lower outside ambient temperature
2. Additional heat transfer due to increased activity
3. Increase airflow around aluminium band

In relation to non-activity, there was a 41.7% increase in voltage generated. In comparison with the TE Collar used in non-activity, activity produce an almost linear graph between the initial instalment and removal where non-activity produced an exponential curve then stabilised to a linear line (see Graph 8.7 trendlines). Further comparisons include a 90% increase in the lowest voltage generated and a 75.6% increase in the average voltage generated. Refer to Table 8.4 to compare non-activity vs. activity.



Graph 8.7 Voltage generated comparisons between active and non-activity with their exponential fitting curve.

Item	Description	TE Collar	
		Non Active	Active (Walking)
1.	Maximum Voltage Generated	1.6 V	2.267 V
2.	Lowest Voltage Generated	0.335 V	0.973 V
3.	Position Temperature (T_h)	33°C	33°C
4.	Ambient Temperature (T_a)	18°C	11°C
5.	Temperature Difference (ΔT)	15°C	22°C
6.	Average Voltage	0.62 V_{avg}	1.089 V_{avg}

Table 8.4 Comparison of performance on level of activity

From these figures it is clear that the TE Collar effectiveness increases with higher activity of the human body since more heat (energy) is been generated and released by the body. Airflow also increases the effectiveness to dissipate heat from the hot side.

Experiment Method #7:

This is a repeat of Experiment 6 but with the heatsinks included. This experiment is designed to determine the TE Collar performance with normal day-to-day activity under ambient temperature and body temperature. The TE Collar was positioned directly on the skin surface of the neck with the heating side to the skin and the cold side exposed to the environment. Heatsinks were attached. The following conditions applied:

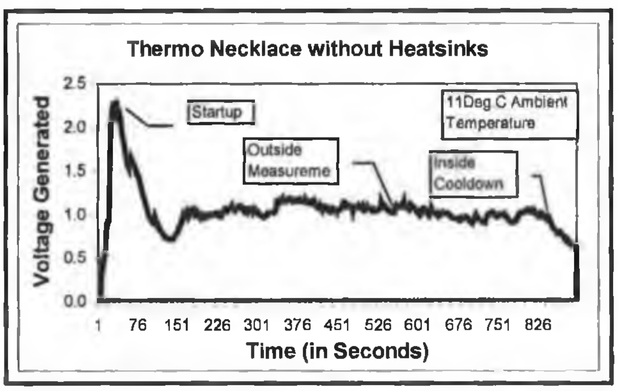
Ambient Temperature (T_2)	11°C (measured)
Skin Body Temperature (T_1)	33°C (measured)
Duration of test	900 seconds
Materials used	Peltier TM Models
Manufacture	TE Technology
Type	TM-TE-63-1.0-2.5P (Potted)

Dimensions (W x L x D)	30mm x 15mm x 3mm
Amount	17 in series connection
Position used	Neck
Heatsink	Included
Measured	Voltage and Ampere
Activity	Low activity- Walking

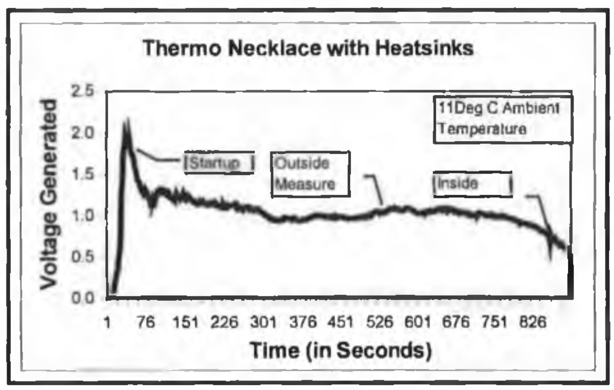
Results of Experiment #7:

This experiment in the outside environment tests the influence of heatsinks attached to the TE Collar. Although the maximum voltage generated is less than without heatsinks, diverse factors influence the start-up measurements. The TE Collar performance with heatsinks is almost identical as the performance without them. This might be explained by the airflow and environmental influences being similar in both the experiments. However, disregarding the start-up and cooldown measurements, the TE Collar average voltage performance, V_{avg}, is greater, more constant and less prone to fluctuations than without heatsinks (see Graph 8.8 & 8.9).

With lesser fluctuations from external conditions, the voltage produced via the DC-DC converter would be less influential.



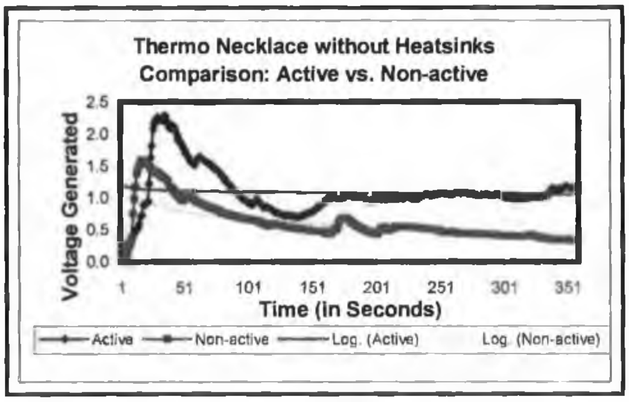
Graph 8.8 Voltage Generated by Thermoelectric Collar Outside Environment excluding Heatsinks



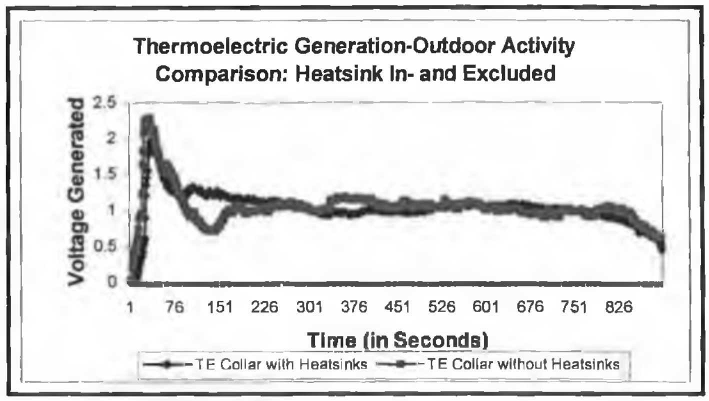
Graph 8.9 Voltage Generated by Thermoelectric Collar Outside Environment including Heatsinks

Item	Description	TE Collar	
		Neck Excluding Heatsinks	Neck Including Heatsinks
1.	Maximum Voltage Generated	2.267 V	1.967 V
2.	Lowest Voltage Generated	0.973 V	0.94 V
3.	Position Temperature (T_h)	33°C	33°C
4.	Ambient Temperature (T_a)	11°C	11°C
5.	Temperature Difference (ΔT)	22°C	22°C
6.	Average Voltage	1.089 V_{avg}	1.111 V_{avg}

Table 8.5 Comparison of performance on outdoor activity (in- and excluding heatsinks)



Graph 8.10 Voltage generated comparisons active and non-activity with their quadratic fitting curve.



Graph 8.11 Voltage generated by Thermoelectric Collar Outside Environment in- and excluding of heatsinks

Experiment Method #8:
This experiment includes the DC-DC Converter with the TE Collar. The experiment is designed to determine the TE Collar performance with normal day-to-day activity under ambient temperature and body temperature. The TE Collar was positioned directly on the skin surface of the neck with the heating side to the skin and the cold side exposed to the environment. The following conditions applied:

Ambient Temperature (T_2)	11°C (measured)
Skin Body Temperature (T_1)	33°C (measured)
Duration of test	900 seconds
Materials used	Peltier TM Models
Manufacture	TE Technology
Type	TM-TE-63-1.0-2.5P (Potted)
Dimensions (W x L x D)	30mm x 15mm x 3mm
Amount	17 in series connection
Position used	Neck
Heatsink	Included
Measured	Voltage and Ampere
Activity	Non- and Low activity (Walking)
DC-DC Converter	Included
Appliances	Single (1.5V) and two cell (3V)

Results of Experiment #8:
The initial results of this experiment were disappointing due to the following reasons:
- Due to non-activity or rest mode of the body, the heat generated by the body was not adequate;
- The heatsinks did not dissipate the heat to the environment due to the lack of movement or airflow, thus reducing the voltage generated;
- The voltage generated was unregulated;
- The voltage generated fluctuated; and
- The lowest voltage generated was not sufficient to excite the DC-DC Converter to boost the voltage.

The experiment was repeated to power single cell (1.5V) appliances. Without the DC-DC Converter, the TE Collar generated sufficient power to drive the appliance for a considerable time. Fluctuations occurred towards the end of the experiment where the voltage generated dropped to below the minimum threshold point (around 1V estimated).

With the DC-DC Converter attached to boost the voltage and output current for the higher requirements of two cell appliances, several conditions were noted. Without the device attached the required voltage was produced. When the appliance was attached to the TE Collar, the voltage dropped immediately below the minimum requirement for the DC-DC Converter to maintain the output voltage. This caused fluctuations between the upper voltage of 4.85V and a lower voltage of 0.9V generated.

This phenomenon might be best explained as a typical regulated waveform: The DC-DC Converter switches continuously at the selected frequency, thus ramping the voltage up to the upper voltage 4.85V and disengaging until the output capacitor is depleted by the appliance load. When the output voltage drops below the lower threshold, the DC-DC Converter switches online again in order to ramp up to the upper output voltage. However, due to the drop in voltage generated over time by the TE Collar, the DC-DC Converter is unable to reach the upper voltage without introducing additional steps in the switching mechanism and thus delaying the upper voltage generation. This cycle increases until the DC-DC Converter is unable to switch from the low voltage produced by the TE Collar, thus causing a upper and lower fluctuation without influencing the power or drive to the appliance. (Also see Chapter 3 for the DC-DC Converter specification)

With this in mind, the following needs to be considered on in order to improve the last results or performance:

1. Improve the heatsinks or introduce alternative cooling mechanisms;
2. Increase the load and therefore the output power from the TE Collar; or
3. Use an alternative type of DC-DC Converter

8.3 Sensitivity Analysis

The multimeter sensitivity and accuracy of the measurements is estimated to be 0.005%. Another consideration is the usage of a Multi-meter in conjunction with TEMs, as this creates an effect similar to another thermocouple in the system; this affects the accurate measurement of the TE Collar.

Model movement with contracting and expanding hot and cold plates was not brought into consideration.

8.4 Efficiencies of the MPTG

In MPTGs the diffusive heat flow and the Peltier effect are additive. Both reduce the temperature gradient and including the resistive voltage drop of the device, the voltage generated due to the Seebeck effect is deducted. Therefore the power generation efficiency η is:

$$\eta = W / Q_H = I\{(\alpha_p - \alpha_n)\,\Delta T - IR\} / K\,\Delta T + (\alpha_p - \alpha_n)\,IT_H - \tfrac{1}{2} I^2 R \qquad (8.1)$$

where:

W power delivered to an external load

Q_H	Heat flow from the source heat sink (positive)
α_p	TE material Seebeck coefficient- positive
α_n	TE material Seebeck coefficient- negative
I	Electrical current
ΔT'	Temperature difference
k	TE material thermal conductivity
K	Conductivity
R	TE module electrical resistance

	W_{max}	η_{max}
I	$(\alpha_P - \alpha_n)\ \Delta T / 2R$	$(\alpha_P - \alpha_n)\ \Delta T / R\ (\gamma + 1)$
R_{Load}	R	$R\ \gamma$
W	$\{(\alpha_P - \alpha_n)\ \Delta T\}^2 / 4R$	$\gamma\ \{(\alpha_P - \alpha_n)\ \Delta T\}^2 / R\ (\gamma + 1)^2$
η	$Z\ \Delta T / (4 + ZT_H + ZT_M)$	$(\gamma + 1)\ \Delta T / \{(\gamma + 1)\ T_H - \Delta T\}$

Table 8.6 Ideal Performance standards for thermoelectric generation [1].

8.5 Summary of Results

In Table 8.7 below, the experimental results are summarised.

Test	**Assembly 1** **TE Collar without Heatsinks**	**Assembly 2** **TE Collar with Heatsinks**
Experiment 1	0.042V	
Experiment 2	1.6V; $0.62V_{avg}$	
Experiment 3	1.292V; $0.56V_{avg}$	
Experiment 4		1.909V; $0.718V_{avg}$
Experiment 5		1.376V; $0.61V_{avg}$
Experiment 6	2.267V; $1.089V_{avg}$	
Experiment 7		1.967V; $1.111V_{avg}$
Experiment 8		0.9V Lower and 4.85V Upper

Table 8.7 Summary of assemblies and correspondence Thermoelectric Generation

8.6 System Dynamics and TE Collar Specification

One of the benefits of Thermoelectric Energy and utilising TEMs for body energy generation is the lightweight construction of the TE Collar. Refer to Table 8.8 below.

Item	**The weight of the TE Collar**	
1.	TE Collar	0.254Kg
2.	DC-DC Converter	0.006Kg
3.	Cable and connectors	0.025Kg
	TOTAL	**0.285Kg**

Table 8.8 Summary of the weight of the TE Collar

Table 8.9 details the design and empirical values or the thermopile requirements. These reflect ideal circumstances of Metal-Metal Thermopiles without resistance and losses in the system:

Metal-to-Metal Thermopiles			
Amount of Thermopiles	n		127
Temperature Hot Junction	T1	34°C	307K
Temperature Cold Junction	T2	20°C	293K
Seebeck Coefficient	Sab		5.000E-05μV/K
Amount of TE Modules			17
Emf generated	Ve		**1.5113V**
Required emf to be generated	Ve		**1.5V**
Temperature Hot Junction	T1	34°C	307K
Temperature Cold Junction	T2	20°C	293K
Seebeck Coefficient	Sab		5.000E-05μV/K
Amount of Thermopiles in module			127
Amount of Thermopiles required	n		**2143**
Amount of Thermocouples required	n		**17**

Table 8.9 Summary of metal-metal thermopiles requirements

8.7 Drawback of Thermoelectric Modules

Similar to the requirements to sustain the human body, thermoelectric modules require a narrow environment to operate. The following drawback was experience during this research:

1. The TEM produces or generates a small amount of voltage.
2. Ambient temperature is almost at the same temperature as the body, therefore low ΔT.
3. Environmental conditions close to and above body temperature will affect performance (like Sahara Desert 55°C) as well as lower extremes like the North and South Poles (-45°C).
4. High temperatures considerably reduce the operational lifetime of TE modules. Contaminants and solder can diffuse into the TE material at high temperatures and degrade the efficiencies and performance or cause failure, this can be controlled by a diffusion barrier.
5. The TEMs require heatsinks or other coolant to create a thermal path in order to increase the generation of electricity supply.
6. Without any voltage or current step-up, the combined TEMs become bulky.

The above needs to be considered as part of the feasible of utilising the TE Collar. Voltage feedback to the TE Collar would influence the TEMs in the TE Collar to operate as normal Peltier devices, however this would only be applicable if a DC-DC Converter is not included due to the protective function of this device. If the voltage feedback is a positive charge, the TE Collar will function as a cooling device, if the voltage feedback is negative, the TEMs will heat up in proportion to the voltage supply, as the TEMs were originally designed.

The DC-DC Converter may be damaged if the feedback network consisting of filter resistors and capacitors receives voltage feedback below –0.5V.

Another consideration is the reaction of the TE Collar to the extreme environments where the body temperature is less than the ambient temperature. In this scenario the

TE Collar voltage reverses and a negative voltage is introduced. The DC-DC Converter reacts to this by rectifying the line voltage or V_{OUT}.

8.8 Heat Transfer, Thermal Control versus TE Output and Temperature Behaviour

The source of heat (the human body) in the ambient environment is constant, the amount of TE power output increases immediately, and then gradually decreases, as the system gets closer to the equilibrium. The temperature (heat transfer rate) gradient drops in a similar slope to the voltage generated ($\Delta T = V$). Due to the initial temperature difference between the ambient environment, (the same initial temperature of the heatsinks and TEMs) and the body skin temperature, the draw-off or heat transfer is at a maximum. This slowly decreases as the temperature difference between the heatsink and the ambient temperature reach equilibrium.

Two types of thermal controls are applicable [1]

1. Thermostatic Control: A thermal load is maintained between two temperature limits.
2. Steady-state control: A thermal load is continuously held at the set-point temperature with very little variation from the set-point

With the initial rise of the thermal load produced by the contact between the TE Collar (at ambient temperature) and the body skin surface, maximum power is generated until the lower temperature rise to equilibrium to the upper temperature. The system would therefore continually vary between the difference between the lower and upper temperature limits in relation to the heat draw-off and dissipation rate. This low and high cycle within the system creates a sysTEMs hysteresis of a small 'ΔT'. This appreciable variation or oscillation can be tolerated in an operating thermal load due to the low impact on the DC voltage generated. Unfortunately, this is mechanically stressful leading to premature aging and failure to the TE modules. This is due to the differential rates of expansion and contraction within the modules.

Since ambient conditions are not constant, sudden changes in ambient or environment conditions will cause the thermal load to quickly adjust to the temperature in terms of the electrical voltage generated. This depends on the cooling capacity of the system to achieve and maintain the amount of current from the TE modules to ensure enough power for the appliance. To accomplish this, the DC-DC Converter must regulate instantaneous variations from the TE current or voltage in response to changes in the ambient environment or thermal load. Therefore the amount of TE power is dependent upon the ambient conditions that may exist at any particular moment.

It should be noted that a buffer might be required for the DC-DC Converter in order to 'power-up' before accepting power from the TE modules. This buffer would ensure the system is not too sensitive and cause over-response to changes in ambient or environmental conditions. This buffer will reduce system oscillation, with the DC-DC Converter output fluctuating up and down and assure stable operation of the system. We assume that the system will always generate more power than the minimum input requirement to drive the DC-DC Converter.

It is possible, upon system 'power-up' that the buffer voltage will contribute to the bulk of the TE power supply while the DC-DC Converter output is charging. This would allow the output of the DC-DC Converter to take over and become the driving force sustaining the necessary level of TE power to the appliances. The higher the initial thermal difference at start-up, the faster the response expected from the buffer voltage.

If the initial thermal difference is inadequate to generate the required voltage, a slow response can be expected without the buffer voltage since the system needs to ramp-up the DC-DC Converter inductor. It was also noted that the TE Collar takes a prolonged period of time to reach the thermal equilibrium. This affects the stability of the DC-DC Converter and the overall regulated output supply.

It might be feasible to increase the switching frequency (Hz in cycles per second) to provide a higher frequency, since lower frequency will increase thermal stresses (effects of thermal expansion and contraction) on the TE modules than higher frequencies will. The drawback however is the potential for electromagnetic interference (EMI) from the high current TE pulses and poor transient responses in the available power supply might cause an audible high frequency noise.

8.9 *Conclusion*

The TE Collar performs extremely well in low temperatures, with a higher temperature difference and increased body activity. Most of the experiments focus on the lowest amount of electricity generated under certain conditions. The best application found for the TE Collar in these conditions was for 1.5V or single cell appliances.

With higher voltages and power requirements the TE Collar struggled to maintain the required voltage output in order to be considered successful. A definite change to the existing layout of the TE Collar is required. In order to be considered successful, a start-up voltage and minimum voltage are required to drive the DC-DC converter in order to maintain the supply of electricity. As discussed above, a buffer supply might be required to overcome this problem.

The only real alternatives than a better heatsink or coolant are a change to the thermoelectric modules themselves. It might be worthwhile to explore a continuous thermoelectric TE Collar without the individual modules. The physical size or dimensions as well as the TEM configuration may need to be adjusted, since the current configuration in series, is only focused at a high output voltage.

With reduced dimensions; a series-parallel configuration will not only improve the current generated by the TE Collar, but higher voltages can be produce with a lower temperature difference. Thus, the effect of voltage supply fluctuations to the DC-DC Converter would be less.

The associated cost to the 'enhanced' performance requirements or sacrifice to the system specification is to be considered. Electrical inefficiencies must be tolerated in order to serve objectives that are more important. The requirements for the TE Collar must be redefined to meet the challenge of adjustability, repeatability, temperature limits or ranges and nature on ability of power output.

In evaluating all the existing conditions, the performance of the TE Collar is satisfactory when compared to the projected or hoped expectations. Although further experiments still need to be performed, this initial research results are adequate to determine that it is feasible to utilise thermoelectric modules for body electricity generation. As a solid-state application, its feasibility was addressed in detail in Chapter 7.

Chapter 9- Summary and Suggestions for Future Activities

9.1 Introduction

In the concept development of the TE Collar, the thinking process in the design identified some of the practical construction issues. However, it is only with the completion of the prototype and with experimentation that the real practical complications became apparent. This design and construction resulted in a learning evolution of corrective and applicable engineering in order to create a functional device.

This Chapter details the mistakes and the lessons learnt for future activities. It does not set out to reinvent the wheel, but to identify considerations that will save time, money and generate a practical solution for the next phase of the MPTG TE Collar development as well as for other thermoelectric applications.

9.2 Summary and suggestions for future activities, Chapter 3

In the previous chapters, reviews of applications and operation of the materials, elements and heat flow of the MPTG were given. Below are a few considerations for possible improvements of the future designs of the MPTG:

9.2.1 Parameters available to improve the device power efficiency

The dimensions, the conductivity, and the geometry of the Peltier devices (working on the Seebeck effect for generation of electricity) are parameters available to improve the power output of the device. This implies the need for a compromise between the power output and optimization of the Peltier device. To summarize, the parameters, which could be used to improve the MPTG performance, are:

1. The thermal resistance layer material and its geometry;
2. The dimension of the gap between the active and the reference junctions;
3. The thickness of the absorber layer;
4. Insulation material between TEMs;
5. Insulation material between heat and cold sink;
6. The length of the thermoelements;
7. Reduction of the ceramic plate thickness; and
8. Improving thermal contacts and properties.

In practical terms, consideration must be given to achieve an increase in the power output by improving the thermal contacts rather than the electrical contacts and or reducing the ceramic plate thickness rather than its thermal conductivity.

9.3 Summary and suggestions for future activities, Chapter 4

The design objectives for thermoelectric modules are:

1. Maximum heat pumping;
2. Maximum coefficient of performance (COP); and
3. Maximum speed of response to absorption and dissipation of heat.

For the above criteria, consideration must be given to the thermal and electrical characteristics of the modules as well as the thermal mass and cooling devices like the incorporated heat sinks.

9.3.1 Heatsinks

A heatsink with a low thermal resistance is preferable, therefore reduction of the heatsink thermal resistance and change of the type or composition of heatsink is recommended. A change in the positioning, orientation and layout of the heatsink will increase the heat dissipation to the ambient environment. Due to the TE Collar layout, the heatsinks were positioned tangent to instead of in line with the horizontal airflow. Although this may be beneficial with natural convection and airflow in a resting or frozen position, heat sinks require airflow around the fins for effective heat dissipation.

Ensure a better thermal interface and contact between the heatsinks and TEM as well as bonding materials to glue these items together.

Loses may be reduced in smaller type of TEMs by increasing contact with the heat and cold sinks. Another consideration would be to omit certain materials in the construction process and incorporate the heatsinks directly on the TEM surface

In the construction process, it was found that the requirement for coldsinks to be in direct contact with the skin not to be a practical application. Exclusion of coldsinks is recommended for the following reasons:

- Coldsinks inefficiencies reduce the amount of heat transfer from the heat source;
- The TEM is directly in contact to the heat source; therefore, maximum heat transfer is possible;
- The overall thickness of the TE Collar is reduced;
- Less material used, therefore there is a reduction of weight and cost of construction;
- The footprint area of the TEM used resulting in less friction to the skin area; and
- No real benefit.

9.3.2 Thermoelectric Modules

TEMs with a higher ΔT_{max}, would generate proportionally higher power. This is the drawback in using Peltier cooling devices for power generation.

The lead wires for the TE modules as supplied by TE Technology Ltd incorporate 58/42 bismuth/tin solder with a melting point of 138°C. The solder used to connect the lead is the normal electronic lead/tin solder with a melting point of 180°C. This mixing of solder types yields inconsistent and detrimental solder properties directly affecting the performance of the TE Collar. For future studies the solder properties used should be the same to 58/42 bismuth/tin solder.

Although widespread applications are limited because of low efficiency, recent research by Heike Scllinschegg, Josua R. Williams, Gene Yoon, David C. Johnson, Micheal Kaeser, Terry M. Tritt, George S. Nolas and E. Nelson has suggested that the efficiencies of these materials can be improved by quantum confinement, i.e. fabricating them in the form of one-dimensional (1 -D) nanowires [3]. The aim is to synthesize nanowires of thermoelectric materials by electrode position and measure the efficiencies of these nanowires.

9.3.3 Thermoelectric Instability

The presence of internal stresses in thermoelements, either because of incomplete annealing or due to their inadvertent introduction, will affect their properties [2]. Instability is the result of chemical non-homogeneities in the TEM thermal properties. Due to the instability, the thermoelectric properties will change as a function of the amount of residual stress temperature, temperature gradient and time.

Homogeneous construction of these TE modules plays a vital role and is affected in the construction phase by temperatures, the materials used including impurities, composition differences and times of exposure. TEMs should be replaced whenever uncertainty arises regarding their stability and integrity. The thermal gradients cannot be change or avoided, but the internal stresses can be manipulated during installation as well as during the use of TEMs.

9.3.4 Heat Transfer

Heat transfer problems in the modules:

1. Transfer of heat between the hot and cold junctions through the space between and around the thermoelements
2. There is a thermal resistance between the hot and cold junctions of the module and the sink and source respectively.

These two functions are related to each other as the space is reduced between the thermoelements which can lead to an increase in thermal resistance as the total cross-section becomes smaller [1].

The length of the hot and cold junctions as well as their cross-sectional area usually affects contact resistance. This can increase the internal electrical resistance (reduce power generated) and add to the thermal load at the hot junction, thus reduce efficiency. It is an economical consideration to keep both the length and cross-sectional area as small as possible. However, at a certain point, the performance of TEMs is affected to such an extent that the increase in the number of thermal elements used offsets any saving in material in each element.

The power output from a thermopile is approximately proportional to its area and inversely proportional to its length. In order to utilise the Peltier device as a generator of waste heat to electrical power, the thermoelement length should be optimised for maximum power output. For power generation, shorter thermoelements lengths are desired due to the coefficient of performance or temperature difference 'ΔT' requirement. The ratio of length and cross-section area affects the contact temperature (see Figure 8.1).

The ceramic layers sandwiched and the thermo structure is affect by as follows:

$$\Delta T = \Delta T_0 / (1 + 2rw) \qquad (9.1)$$

Where:

ΔT Actual temperature difference across thermoelements

ΔT_0 Applied temperature difference

r Ratio of thermal conductivity when $r = \lambda / \lambda_c$

w Ratio of ceramic thickness and thermoelements when $w = L_c / L_0$

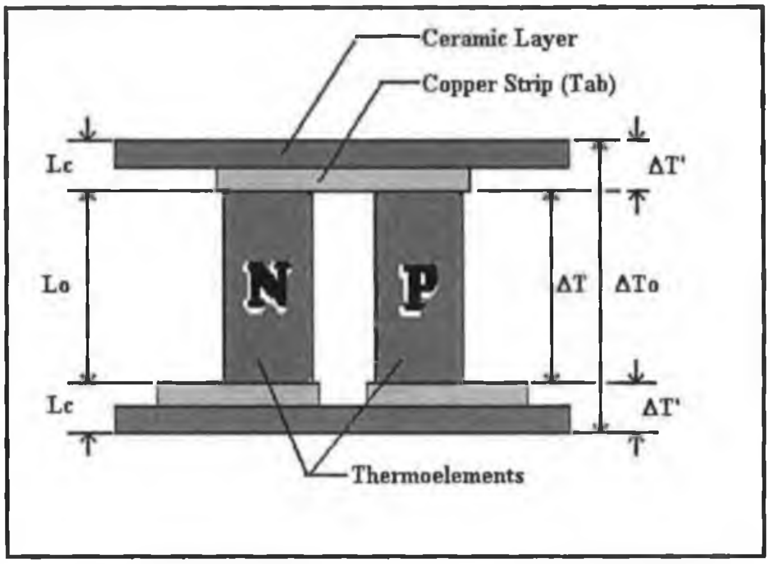


Figure 9.1 Schematic diagram of realistic Peltier Device

Most commercially available Peltier devices, such as the ones used in the experiments of this thesis, have been optimised to attain the largest temperature difference or coefficient of performance.

9.3.5 New Materials for Thermoelectric Applications

The introduction of Chapter 4 highlights the basic requirement for good semiconductor material suitable for thermoelectric power generation. The essence of a good thermoelectric is given by the determination of the material's dimensionless figure of merit 'ZT' where thermoelectric materials must combine a large Seebeck coefficient 'α' with a low electrical resistivity 'ρ_e' and thermal conductivity 'κ':

$$ZT = (\alpha^2 \rho_e / \kappa)T \qquad (9.2)$$

To incorporate the above criteria into one material remains to be seen [1]. However, in search for new thermoelectric materials, one approach is to 'identify' semiconductor compounds that have good electronic properties and very low thermal conductivity values. The thermal conductivity consists of two parts, the electronic and the lattice thermal conductivity. The best thermoelectric materials to date have a value of $ZT \approx 1$, which has been an upper limit for more than 30 years.

Traditionally, the use of high temperatures to directly combine elements or simpler compounds into more complex ones has proven to be successful in providing new materials. However, this approach gives rise to key synthetic limitations since the reactions mostly progress to the most thermodynamically stable products. These thermodynamically stable products are typically the simplest binary or ternary compounds, and because of their high lattice stability, they become synthetic obstacles. These high reaction temperatures also dictate that only the simplest chemical building blocks can be used. Synthetic attempts using molecules of known structure are doomed because the high temperatures reduce the system to a thermodynamic minimum, thereby not alloying for the desired bond formation. Hence, multinary compounds can be more difficult to form, and the preference lies with more stable binary and ternary compounds [1].

Another approach has been to perform reactions using molten salts as solvents. Such media have been employed for more than 100 years for high-temperature, single-crystal growth [1]. Although many salts melt at high temperatures, eutectic combinations of binary salts and salts of polyatomic species often have melting points well below the temperatures of classical solid-state synthesis, making possible their use in exploring new chemistry at intermediate temperatures. In many cases, such salts act as solvents and also as reactants, providing species and building blocks that can be incorporated into the final product.

The structural and compositional complexity can result in corresponding complexities in electronic structure that may produce beneficially large asymmetry in the density of states to obtain large values of the Seebeck coefficient 'α'. The contribution to thermal conductivity 'λ' can also be reduced by such structural complexity, by choosing heavy elements, and by choosing combinations of elements that make moderate to weak chemical bonds. In such materials, a weakly bound atom or molecule can create localised dynamic disorder thereby resulting in a low 'λ' value for the solid material without severely affecting the electronic conduction and potentially leading to improved thermoelectric materials. The fact that alloys of Bi_2Te_3 and Bi-Sb are the best thermoelectric materials known to date, below 100°C suggests that they possess features necessary for high figures of merit. It can be reasoned that similar properties may manifest in similar compounds. Therefore research is directed to explore other multinary chalcogenides of bismuth and antimony in the hope that these elements will impart some (or all) of the key properties needed for superior thermoelectric materials [1].

A new version of a segmented thermoelectric 'unicouple' proposed by T. Caillat, J. P. Fleurial, G. J. Snyder, and A. Borshchevsky, incorporating advanced thermoelectric materials with superior thermoelectric figures of merit has been recently proposed and is currently under development at the Jet Propulsion Laboratory (JPL) California Institute of Technology [3]. This advanced segmented thermoelectric unicouple includes a combination of state-of-the-art thermoelectric materials based on Bi_2Te_3 and novel materials developed at JPL. The segmented unicouple currently developed expected to operate between 300 and about 975K with a projected thermal to electrical efficiency of up to 15%. The segmentation can adjust to accommodate various hot-side temperatures depending on the specific application envisioned. Techniques and materials been developed to bond the different thermoelectric segments together for the n- and p-legs and low contact resistance bonds have been achieved.

Each section of the unicouple has the same current and heat flow as the other segments in the same leg. Thus in order to maintain the desired temperature profile the geometry of the legs must be optimized. Specifically, the relative lengths of each segment in a leg must be adjusted, primarily due to differences in thermal conductivity, to achieve the desired temperature gradient across each material. The ratio of the cross sectional area between the n-type and p-type legs must also be optimized to account for any difference in electrical and thermal conductivity of the two legs. At each junction (cold, hot, or interface between two segments), the relative lengths of the segments are adjusted to ensure heat energy balance at the interface. Without any contact resistance between segments, the overall length of the device does not affect the efficiency; only the relative length of each segment needs to be optimized. The total resistance and power output, however, does not depend on the overall length and cross section area of the device [1].

It is understood that the future advances in thermoelectric applications will come through research in new materials, instead of further optimization of established materials.

9.4 Summary and suggestions for future activities, chapter 5

Utilising the human body as a heat source to drive a thermoelectric generator involves heat transfer from the body to the generator. Temperature difference across the interface between the body and the device exists. Due to the extra thermal resistance that exists between the body and the solid interface, the thermoelectric length has to be re-optimised to take into account the temperature drops at the body-device interface.

The body's natural magnetism fields may be disrupted by the MPTG and result in nerve disorder or degrading cell structure. This needs to be studied in more detail and for future consideration. Other considerations include restrictions on blood flow, claustrophobia , restriction on breathing and swallowing, neck movement, and friction between the MPTG and the neck or leg skin.

9.5 Summary and suggestions for future activities, Chapter 6 & 7

The thermoelectric generation feasibility assessment, its impact and environmental consequences are already addressed in detail in their respective chapters.

9.6 Summary and suggestions for future activities, Chapter 8

9.6.1 Revised TEM strap and skin contact

During the experiments in Chapter 8, it become apparent that the flexibility of the TE Collar seriously restricts full contact of the TEMs with the skin. It was noted that not all the TEMs were not in full contact with the skin at the same time, which impacted on the effectiveness of the TE Collar. To mitigate this problem, it is proposed to discard the aluminum band in favor of a nylon strap and place the TEMs directly on the skin. This will ensure full adjustability and contact on the skin area.

Another consideration is to cover the sharp edges of the TE module ceramics or incorporate safety aspects in order to minimize skin abrasion. This may be achieved by a different TE Collar layout as proposed above.

9.6.2 Future Experiments

The TE Collar requires future experiments to be conducted in the range of ambient temperatures from 1°C to 40°C and a constant body temperature at 33°C. These temperature ranges simulate the voltage produced under a broader temperature range and outside conditions.

The TE Collar also needs airflow simulation from zero to 8m/s (to monitor airflow velocities and conditions around the TE Collar) with normal ambient temperature to simulate normal active body temperature and airflow/wind around the TE Collar and the voltage produced under these conditions. Future study is required on the following variables:

1. Temperature vs. voltage generated;
2. Airflow vs. voltage generated;
3. Airflow and Temperature vs. voltage generated; and
4. Temperature during cool-dry/ hot-sweaty conditions to be monitored.

9.7 Possible applications of the MPTG in the industry

Although most of the general application areas of Miniature Personal Thermoelectric Generator have been discussed in chapter 3, here we will expand on other basic applications.

With the increase of technology, regulations and legislations, the workforce usage of electronic devices like computers, monitoring and communication equipment is a daily job function. This applies to miners, offshore personnel, farmers, occupations in remote locations, rescue personnel, adventure sports such as mountain climbing or cycling, soldiers or even businessmen and in educational centers.

The usage and requirement of electronic devices has increased and there is more and more demand for reliable and individual power sources. One such example is the mobile or cell phone which is not only used for communication but is also a fashion statement or craze.

9.8 Storage of the MPTG Energy

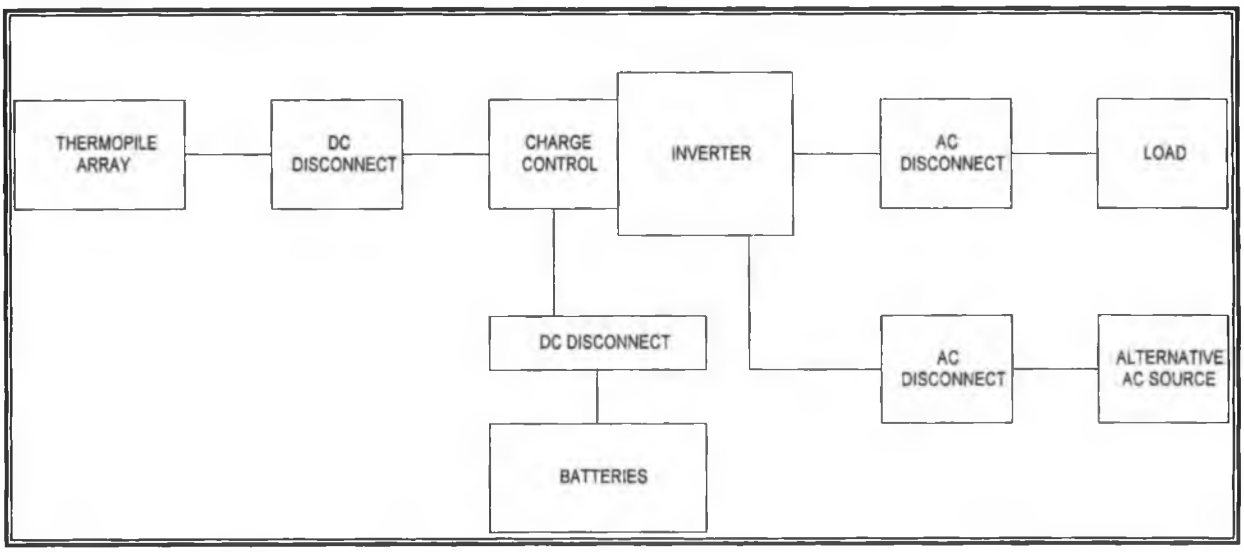


Figure 9.2 Inverter Schematic of hybrid energy system

If a storage vessel for heat or electricity, like a rechargeable battery, can be incorporated to store heat energy over a certain period, the TE Collar may benefit. Figure 9.2 shows a typical schematic of such a system for the TE Collar or similar thermoelectric applications.

9.9 Possible future utilization of TEMs

In Chapter 3, references were made to several current applications for thermoelectric generation. Past and current applications of TEM focus mainly on heat-to-power generated by incorporated energy sources. Very little focus exists on waste heat. In the original thesis development, initial focus was on industrial waste, solar and human energy. It is of interest only to expand on these ideas.

9.9.1 Solar Energy Utilisation

The Author proposes to utilise solar energy by focusing or concentrate sunlight through magnifying glass and mirrors on the TEM. The concept is to create a reflective shield to reflect light/heat away from heat sinks while concentration sunlight on the TEMs.

The thermopile utilizes the sunlight through a number of thermoelectric modules placed as an 'absorber'. The sunlight strikes the 'absorber' and heats it up to generate a voltage at the output leads. The output is a DC voltage which is a direct measure of the incident radiation power, P_{rad}. Due to the low voltage produced, amplification will be required in the form of a DC-DC or DC-AC converter. Refer to Figure 9.3 below.

The application may be more suited as a hybrid energy system as proposed in Figure 9.2 where solar energy is the main energy source at daytime and energy storing buffers (water ponds or tanks) may be incorporated to be heated up by solar energy and to be utilized for nighttime generation.

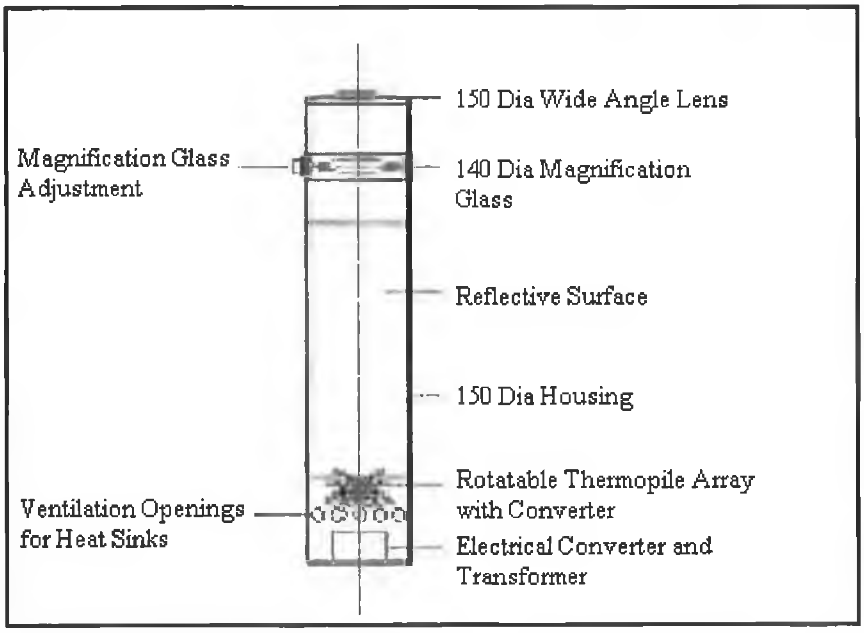


Figure 9.3 Schematic of Author's proposal to utilize solar energy

This storage of heated water is to be circulated to the reflective shield to utilise the nighttime temperature difference of the heated water in order to create electricity via the TEMs.

9.9.2 Industrial and Commercial Waste Heat Utilisation

Most industrial utilise boilers for production process or in the commercial application for central heating and hot water. Boiler emissions range from 11% unused condensed heat, 7.4% flue gas losses and less than 0.1% of radiation losses.

With a design boiler load of 2500kW for commercial applications, the loss of waste heat through the flue would be about 185kW. For every $1m^2$ of heating for commercial buildings, the design-heating load would be about $120W/m^2$ according to

CIBSE design loads. This means the loss per square meter would be 1,126W/m^2 due to flue waste heat emissions.

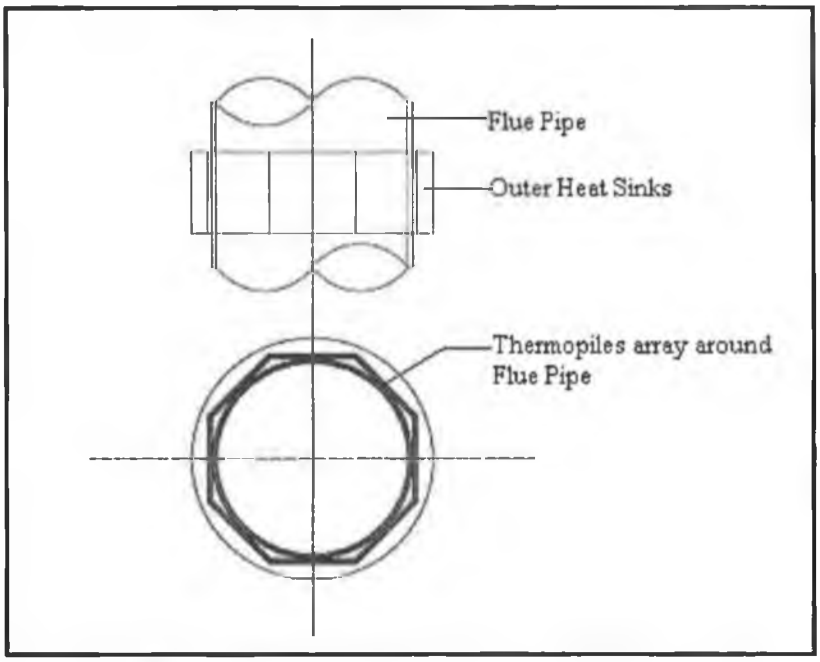


Figure 9.4 Schematic of Author's proposal to utilize flue waste energy

In industrial applications for glass, plastic and manufacturing plants, the efficiencies of boilers and the loss due to flue emissions is greater.

A section or area of a flue pipe will be used to install the thermoelectric modules. The thermocouples will be installed around the circular flue or duct in series and include heat sinks on the outside. Refer to Figure 9.4.

The second phase of this installation is to connect a converter to the TEMs to boost the voltage output. If the full area of the flue section can be covered with TEMs, the combination hopefully would generate enough current to be utilised again into the industrial electrical supply system.

9.9.3 Power Plants and other Facilities Waste Heat Utilisation

Electric power plants and other large industrial utilities contain significant amounts of low-temperature energy in the form of cooling water. Some of the waste energy is used to heat the cooling water in the excess of 40°C which is adequate to be used as a low-grade heat source for thermo electrical applications.

The cooling water from larger blast furnaces is heated to a temperature of approximately 95°C. It is estimated that a wastewater throughput of 1m^3/s would provide around 10 MW of electrical power. Thermoelectrically recovered waste heat would be sufficient to meet the on-site electrical requirements [5].

9.9.4 Geothermal and Ocean Utilisation

Utilisation of geothermal or temperature difference from the ocean is based on possible the same concept as for the industrial waste heat application. In the oceans, thermal layers exist. The best applications to use the ocean thermal energy are in the

Polar Regions or near the equator where the temperature difference is the highest in relation to surface and sub-surface temperatures. See Figure 9.5 for a thermal pump generator suitable to use for such applications.

Other considerations are redundant oil platforms for ocean thermal energy and abandon shaft mines for geothermal energy.

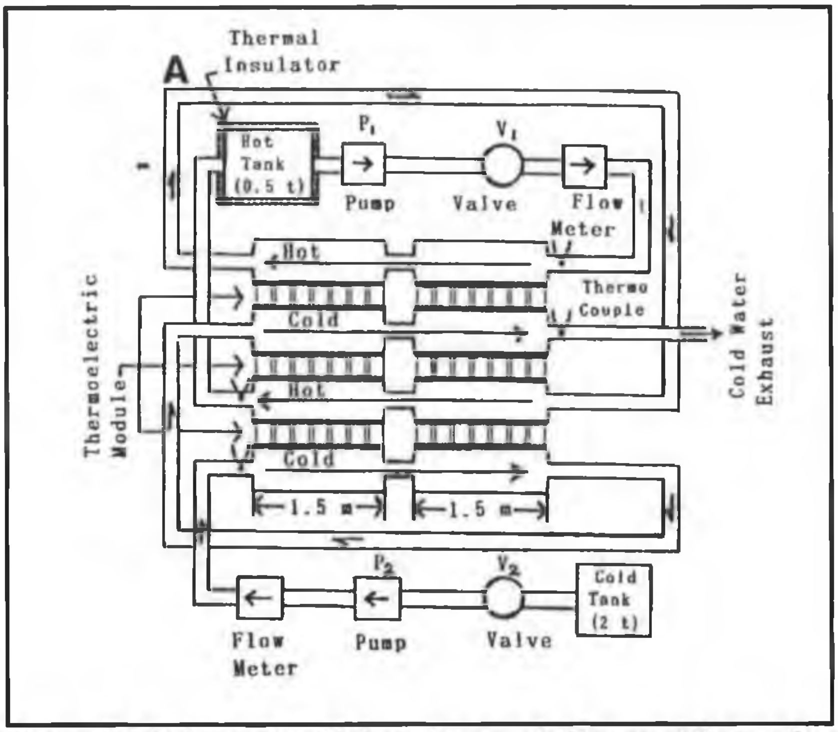


Figure 9.5 Schematic of laboratory-scale Thermal Pump Generator [5]

To convert the redundant platforms to thermoelectric power stations, hot water pumped under pressure from the oil-exhausted reservoirs or mine shafts to above where the hot water converts to steam with reduction of pressure at the surface and drives turbine electric generators on the platform. The electricity generated is transmitted to the main grid system. This available hot water at low-temperature heat can be converted into electricity using thermoelectric generators [5].

9.10 Conclusion

Despite this extensive investigation to utilize traditional thermoelectric materials for power generation, there is still substantial room for improvement with entirely new classes of compounds and manufacturing techniques. Efficient TE materials at lower temperatures could eventually lead to thermoelectric modules that would greatly aid in generating human power devices such as the TE Collar. The efficiency of a thermoelectric material is commonly determined by the dimensionless figure of merit, ZT, (refer to equation 9.2) influenced by the Seebeck coefficient (or thermopower), electrical conductivity, electrical resistivity, temperature, and the thermal conductivity. The ideal is to maximized thermopower to increase the Peltier effect. Electrical resistivity should be kept small to minimize the Joule heating (I^2R) contribution. The thermal conductivity in a good thermoelectric material should be relatively low so that a temperature difference, 'ΔT', may be established and maintained across the material. An ideal thermoelectric material should exhibit a large amount of phonon scattering to minimize thermal conduction and a small amount of electron scattering to maximize electrical conduction [3]. Low temperature thermoelectric materials are even more difficult to achieve, since the absolute value of the thermopower typically decreases with decreasing temperature.

Consequently, changes in the electrical conductivity will affect the electronic thermal conductivity. Achieving high thermopower at low temperatures is one of the important issues for discovering or optimizing thermoelectric materials for low temperature applications such as proposed in this thesis. However, the results from the experimental investigations in Chapter 8 concluded that it is feasible to utilize current TE materials and Peltier devices for the application of generate electricity via body heat.

Chapter 10- Conclusions

Application of the Peltier thermoelectric module is endless. Some of the practical considerations and implications were discuss in previous chapters. The technology for fabricating thermoelectric devices, which generate milliwatt of electrical power at relatively high voltage using traditional thermocouples, is well established. Thermoelectric materials and energy is environmentally "friendly" and used in a wide variety of applications related to small-scale solid-state refrigeration or power generation. However, this device's application is restricted to situations where their proven reliability and specific characteristics outweighs their relatively low efficiency and high cost.

The variables to the TE Collar; thermoelectric materials, the human body, environmental conditions and the make-up of the TE Collar influence the outcome of the power generated.

The drawback of the proposed human power device is the influence of ambient environment as well as the human activity required to keep the voltage generated high enough for the DC-DC Converter to reduce fluctuations of the output for higher voltage requirements. With the development of newer materials and efficiency increase, the environmental impact in terms of ambient conditions will greatly influence the TE Collar's performance. It is however noteworthy to add that heat sinks and the airflow rate influences the voltage positively. It become apparent in the evaluation phase the size of the collar and the TE modules need to be reduced in order to introduce more TEMs to the system. This will encourage the system to stabilise at a higher voltage output.

The TE Collar used in the experiments was a crude but vital model in the learning process for a realistic assembly of such a device. In future, several realistic issues need to be addressed. The first and most important issue is cost. Although the initial cost is high in comparison to batteries, the cost will substantially decrease with mass-production, with alterations to the TE Collar layout and reductions to the TEMs (less material used). Like any technology, the TE Collar will become less expensive over time with refinement and recognition by consumers. Overall, the TE Collar generation cost compares quite favorable to conventional power sources.

The second issue is the feasibility. What it can do and what it cannot do, and what are the benefits? The TE Collar is a commodity and its real strength is in its novelty as a stand-alone device to generate electricity under diverse conditions and situations. It is a secure form of energy that reduce the dependency on battery power. Its prevalent acceptance is the application as renewable energy and impact on the environment.

The third issue is the question on safety aspects to be included. The DC-DC Converter already incorporates safety aspects in terms of the integrated circuit electronics (see Chapter 4). The affect on health would be even less than a cell or mobile phone would have as the only aspect would be the skin contact and the waste heat directed away from the body. The position of the TE Collar around the neck would still be consider as the best position for such a device due to the un-obstructive airflow and maximum heat transfer from the body to the environment.

Finally, the development of integrated circuit technology for the microelectronics industry and new TE materials (especially quantum wires and thin film TE developments) has provided an ideal improvement for the miniaturization of generators as proposed in this thesis. Both devices can be mass-produced with reproducible performance. Future developments in thermoelectric technology are assuring with the commercial market expanding rapidly on a broad front. Integrated circuit technology enables miniature low-power, high-voltage devices like the DC-DC Converters to be incorporate into a semiconductor chip.

However, future development in microelectronics lean towards smaller circuits and are likely to be accompanied by a requirement for a localised integrated power and voltage source as proposed by this human body heat-to-power application. This application will soon change many usages and eventually our way of living. The design of the TE Collar may be in the early stage of developing a practical usage and harnessing of human energy. This might be the governing individual low-power source for the future.

Chapter 11- Appendix

11.1 Summary of Definitions and Terminology

AMBIENT TEMPERATURE: Temperature of the air or environment surrounding a thermoelectric cooling system; sometimes called room temperature.

ASPECT RATIO: The numerical ratio of the length (height) to cross-sectional area of a thermoelectric element. An element's L/A aspect ratio is inversely proportional to its optimum current.

BIOENERGETICS: The quantitative analysis of how organisms gain and use energy.

BISMUTH-ANTIMONY: A thermoelectric semiconductor material that exhibits optimum performance characteristics at relatively low temperatures.

BISMUTH TELLURIDE: A thermoelectric semiconductor material that exhibits optimum performance in a "room temperature" range. An alloy of bismuth telluride is used most often for thermoelectric cooling applications.

BTU: British Thermal Unit: The amount of thermal energy required to raise one pound of water by one degree Celsius at a standard temperature of 15°C.

CALORIMETER: A scientific apparatus used to measure the evolution or absorption of heat. Thermoelectric modules, when used in a calorimeter, may exhibit much higher sensitivity than conventional thermopiles.

CASCADE MODULE (MULTI-STAGE MODULE): A thermoelectric module configuration whereby one module is stacked on top of another so as to be thermally in series. This arrangement makes it possible to reach lower temperatures than can be achieved with a single- stage module.

CHEMICAL POTENTIAL: (also called partial molar free energy). In a system, this is the free energy that resides in a chemical component per mole of the component present. For example, in a system consisting of 'a' moles of component A and 'b' moles of component B, the total free energy 'G' would be the sum of the free energy in the two components.

CFM: Cubic Feet per Minute: The volumetric flow rate of a gas, typically air, expressed in the English system of units. For thermoelectric applications, this generally refers to the amount of air passing through the fins of a forced convection heat sink.

CLOSED-LOOP TEMPERATURE CONTROLLER: A temperature controlling device with some type of temperature sensor (thermocouple, thermistor, RTD, etc.) that will transmit or "feed back" temperature data to the controller. Based on the returned information, the controller will automatically adjust its output to maintain the desired temperature.

COEFFICIENT OF PERFORMANCE (COP): A measure of the efficiency of a thermoelectric module, device or system. Mathematically, COP is the total heat transferred through the thermoelectric device divided by the electric input power. COP sometimes is stated as COPR (Coefficient of Performance as a Refrigerator) or as COPH (Coefficient of Performance as a Heater).

COLD SIDE OF A THERMOELECTRIC MODULE: The side of a module that normally is placed in contact with the object being cooled. When the positive and negative module leads are connected to the respective positive and negative terminals of a DC power source, heat will be absorbed by the module's cold side. Typically, the leads of a TE module are attached to the hot side.

CONDUCTION (THERMAL): The transfer of heat within a material caused by a temperature difference through the material. The actual material may either be a solid, liquid or gas (or a combination) where heat will flow by means of direct contact from a high temperature region to a lower temperature region.

CONVECTION (THERMAL): The transfer of heat by means of air (gas) movement over a surface. Convection is actually is a combined heat transfer process that involves elements of conduction, mixing action, and energy storage.

COUPLE: A pair of thermoelectric elements consisting of one N-type and one P-type connected electrically in series and thermally in parallel. Because the input voltage to a single couple is quite low, a number of couples normally are joined together to form a "module."

DEGREES KELVIN: Absolute temperature scale where absolute zero (0K) represents the point where all molecular kinetic energy of a mass is zero. When calculating the temperature dependent properties of semiconductor materials, temperature values must be expressed in degrees Kelvin. On the Celsius scale, 0˚C equals 273.15K; in respect to quantity, one Kelvin degree equals one Celsius degree. Note that the (°) symbol normally is not used when denoting degrees Kelvin.

DELTA-T: The temperature difference between the cold and hot sides of a thermoelectric module. Delta T may also be expressed as "ΔT" or "DT."

DENSITY: The mass of a material per unit volume; often expressed as pounds per cubic foot or grams per cubic centimetre.

DICE: A general term for blocks of the thermoelectric semiconductor material or "elements" prepared for use in a thermoelectric module.

DIE: An individual block of thermoelectric semiconductor material used in the fabrication of a module. A die may also be called an "element," "leg," or "thermoelement".

ENDERGONIC: In a non-isolated system a process that is accompanied by a positive change in free energy (ΔG) and therefore is not thermodynamically favoured.

EFFICIENCY: For thermoelectric coolers, mathematical efficiency is the heat pumped by a module divided by the electrical input power; for thermoelectric generators, efficiency is the electrical output power from the module divided by the heat input. To convert to percent, multiply by 100. See definition of Coefficient of Performance.

ELEMENT: An individual block of thermoelectric semiconductor material. See definition of DIE.

EMISSIVITY: The ratio of the energy emitted by a given object to the energy emitted by a blackbody at the same temperature. Emissivity is dependent upon an object's material and surface finish. Also the body radiating energy at a temperature is equal to absorptivity of the body when receiving energy from a source at a temperature

ENERGY: Energy is the physical quantity where, in the context of thermoelectrics, generally is used to express a unit of heat or electricity. Energy may be stated in British Thermal Units (BTU) or watt-hours. It is important to note the difference between energy and power. Power is the rate at which energy is being used, and power may be stated in BTU/hour or watts. The relationship between power and energy is Power = Energy / Time.

ENTHALPY: A thermodynamic quantity (function of state) symbolized by H that is equal to the internal energy of a system plus the product of the pressure and volume: $H = E + PV$. It is equal to the heat change in constant-pressure reactions

ENTROPY: A thermodynamic quantity (function of state) that expresses the degree of disorder or randomness in a system. According to the second law of thermodynamics, in an open system, this tends to increase unless energy is expended to keep the system orderly.

EXERGONIC: In a non-isolated system, a process that is accompanied by a negative change in free energy (ΔG) and therefore is thermodynamically favoured.

FIGURE-OF-MERIT (Z): A measure of the overall performance of a thermoelectric device or material. Material having the highest figure-of-merit also has the highest thermoelectric performance.

FIRST LAW OF THERMODYNAMICS: The law that states that energy cannot be created or destroyed and that it is therefore possible to account for any change in the internal energy of a system ΔE by an exchange of heat (q) and/or work (w) with the surroundings. $\Delta E = q - w$.

FORCED CONVECTION HEAT SINK: A heat sink that incorporates a fan or blower to actively move air over the heat sink's fins. Greatly improved cooling performance may be realized with a forced convection system when compared to a natural convection heat sink

FREE ENERGY (G): A thermodynamic quantity (function of state), symbolized by G, that takes into account both enthalpy and entropy: $G = H - TS$ where H is enthalpy, S is entropy, and T is absolute temperature. The change in this quantity (ΔG) for a process, such as a chemical reaction, takes into account the changes in enthalpy and entropy and indicates whether the process will be thermodynamically favoured at a given temperature

HEAT LEAK: The amount of energy gained or lost by an object being thermoelectrically controlled due to heat transfer to or from external media. Heat transfer may occur due to conduction, convection, and/or radiation.

HEAT LOAD: The quantity of heat presented to a thermoelectric device that must be absorbed by the device's cold side. The term heat load, when used by itself, tends to be somewhat ambiguous and it is preferable to be more specific. Terms such as active heat load, passive heat load or total heat load are more descriptive and specific.

HEAT OF FUSION: More correctly called Latent Heat of Vaporization. The amount of heat energy required to change a given mass of a substance from a liquid to a gas without changing the temperature of the substance. To change water into stream, for example, requires a heat input of about 971 BTU/pound or 540 calories/gram.

HEAT PUMP (THERMOELECTRIC): A general term describing a thermoelectric cooling device, often being used as a synonym for a thermoelectric module. In somewhat less common usage, the term heat pump has been applied to a thermoelectric device operating in the heating mode.

HEAT PUMP (THERMODINAMIC): The action where energy is transferred against the natural temperature gradient from a low temperature to a higher. When the net heat supplied to the system from its surroundings is equal to the net work done in a thermodynamic cycle. In terms of refrigeration, this is the energy rejected by the refrigerant for heating purposes.

HEAT PUMPING CAPACITY: The amount of heat that a thermoelectric device is capable of pumping at a given set of operating parameters. Frequently, this term will be used interchangeably with the *expression maximum heat pumping capacity*. The two terms are not strictly synonymous, however, because maximum heat pumping capacity specifically defines the maximum amount of heat that a module will pump at the maximum rated input current and at a zero temperature differential.

HEAT SINK: A body that is in contact with a hotter object and that expedites the removal of heat from the object. Heat sinks are typically intermediate stages in the heat removal process whereby heat flows into a heat sink and is then transferred to an external medium. Common heat sinks include natural (free) convection, forced convection and fluid cooled.

HEAT TRANSFER COEFFICIENT: A numerical value that describes the degree of coupling that exists between an object and a cooling or heating fluid. The heat transfer coefficient is actually an extremely complex value that encompasses many physical factors.

HEIGHT TOLERANCE (MODULE): The maximum variation in height or thickness of a thermoelectric module referenced to its nominal specified dimension. Most Ferrotec modules are available in two tolerance ranges of ±0.03mm and ±0.3mm. When more than one module will be installed between a given pair of mounting surfaces, the maximum height variation of all modules should not exceed 0.06mm.

HOT SIDE OF A THERMOELECTRIC MODULE: The face of a thermoelectric module that usually is placed in contact with the heat sink. When the positive and negative module leads are connected to the respective positive and negative terminals of a DC power source, the module's hot side will reject heat. Normally, the wire leads are attached to the hot side ceramic substrate.

INTERSTAGE TEMPERATURE: The temperature between specific stages or levels of a multi-stage or cascade module.

JOULE HEATING: Heat produced by the passage of an electrical current through a conductor or material due to the internal resistance.

KILOCALORIE (kcal): The calorie is the amount of energy required to raise the temperature of 1000g (1kg) of water from 14°C to 15°C. One calorie = 4.184 joules

KINEMATIC VISCOSITY: The ratio of a fluid's viscosity to its density; typically units are centimetres squared per second and feet squared per second.

LATENT HEAT: Thermal energy required to initiate a change of state of a substance such as changing water into ice or water into steam.

LEAD TELLURIDE: A thermoelectric semiconductor that exhibits its optimum performance within a temperature range of 250-450°C. Lead telluride is used most often for thermoelectric power generation applications.

LIQUID COOLING: A heat sink method involving the use of water or other fluids to carry away unwanted heat. When comparing alternative heat-sinking methods, liquid cooled heat sinks normally provide the highest thermal performance per unit volume.

MASS FLOW RATE: The weight of a fluid flowing per unit of time past a given cross-sectional area. Typical units include pounds per hour-square foot and grams per second-square centimetre.

MAXIMUM TEMPERATURE DIFFERENTIAL (MAXIMUM DT): The largest difference that can be obtained between the hot and cold faces of a thermoelectric module when heat applied to the cold face is effectively zero. DT_{max} or D_{max} is one of the significant thermoelectric module/device specifications.

MAXIMUM HEAT PUMPING CAPACITY (MAXIMUM Qc): The maximum quantity of heat that can be absorbed at the cold face of a thermoelectric module when the temperature differential between the cold and hot module faces is zero and when the module is being operated at its rated optimum current. Q_{max} is one of the significant thermoelectric module/device specifications.

MODULE: A thermoelectric cooling component or device fabricated with multiple thermoelectric couples that are connected thermally in parallel and electrically in series.

MULTI-STAGE MODULE (CASCADE MODULE): A thermoelectric module configuration whereby one module is mechanically stacked on top of another so as to be thermally in series. This arrangement makes it possible to reach lower temperatures than can be achieved with a single-stage module.

NATURAL CONVECTION HEAT SINK: A heat sink from which heat is transferred to the surrounding air by means of natural air currents within the environment. No external fan, blower or other appliance is used to facilitate air movement around the heat sink.

N-TYPE MATERIAL: Semiconductor material that is doped so as to have an excess of electrons.

OPTIMUM CURRENT: The specific level of electrical current that will produce the greatest heat absorption by the cold side of a thermoelectric module. At the optimum current, a thermoelectric module will be capable of pumping the maximum quantity of heat; maximum temperature differential (DT_{max}) typically occurs at a somewhat lower current level.

PELTIER EFFECT: The phenomenon whereby the passage of an electrical current through a junction consisting of two dissimilar metals results in a cooling effect. When the direction of current flow is reversed heating will occur.

PHASE CHANGE: The change of a substance from a liquid to solid, liquid to gas, etc. A phase change occurs, for example, when water freezes and turns into ice. See Heat of Fusion.

POWER SUPPLY: Any source of DC electrical power that may be used to operate a thermoelectric device.

P-TYPE MATERIAL: Semiconductor material that is doped so as to have a deficiency of electrons.

RADIATION (THERMAL): The transfer of heat energy by electromagnetic waves as a result of a temperature difference between two bodies. In thermoelectric cooling applications, radiation losses are quite small and usually have to be considered only for multi-stage coolers operating near a DT_{max} condition.

RESISTIVITY (ELECTRICAL): Resistivity is a bulk or inherent property of a material that is unrelated to the physical dimensions of the material. Electrical resistance, on the other hand, is an absolute value dependent upon the cross-sectional area (A) and Length (L) of the material. The relationship between Resistivity (r) and Resistance (R) is: $r = (A/L)\,(R)$

SECOND LAW OF THERMODYNAMICS: The law that states that the entropy in a closed system never decreases. An alternative statement is that processes that are thermodynamically favoured at constant temperature and pressure involve a decrease in free energy.

SEEBECK EFFECT: The phenomenon whereby an electrical current will flow in a closed circuit made up of two dissimilar metals when the junctions of the metals are maintained at two different temperatures. A common thermocouple used for temperature measurement utilizes this principle.

SI: An abbreviation for System International, the international standard metric system of units.

SILICON-GERMANIUM: A high temperature thermoelectric semiconductor material that exhibits its optimum performance within a temperature range of 500-1000°C. Silicon-Germanium material most often is used for special thermoelectric power generation applications that utilize a radioisotope/nuclear heat source

SINGLE-STAGE MODULE: The most common type of thermoelectric cooling module using a single layer of thermoelectric couples connected electrically in series and thermally in parallel. Single-stage modules will produce a maximum temperature differential of approximately 70°C under a no-load condition.

SPECIFIC GRAVITY: The ratio of the mass of any material to the mass of an equal volume of water at a temperature of 4˚C.

SPECIFIC HEAT: The amount of thermal energy required to raise the temperature of a given substance by one degree compared to the energy required to raise the temperature of an equal mass of water by one degree. The specific heat of water is 1.000.

STATE: A term defining the important parameters of a system. Thermodynamically, it is defined by prescribing the amounts of all substances present and any two of the following three variables: the temperature (T), the pressure on the system (P), and the volume of the system (V).

SUBSTRATE: A plate or sheet of thermally conductive and electrically insulated material on which a thermoelectric module is fabricated. A typical module has two individual substrates each having a metalized pattern to conduct electric current. Thermoelectric elements are sandwiched between the two substrates to form a completed module. Most substrates used in thermoelectric coolers are made of alumina ceramic although berylia ceramic and other materials may be used in special circumstances.

THERMAL COEFFICIENT OF EXPANSION: A measure of the dimensional change of a material due to a change in temperature. Common measurement units include centimeter per centimeter per degree Celsius and inch per inch per degree Fahrenheit.

THERMAL CONDUCTANCE: The amount of heat a given object will transmit per unit of temperature. Thermal conductance is independent of the physical dimensions, i.e., cross-sectional area and length of the object. Typical units include watts per degree Celsius and BTU per hour per degree Fahrenheit.

THERMAL CONDUCTIVITY: The amount of heat a material will transmit per unit of temperature based on the material's cross-sectional area and thickness.

THERMAL GREASE: A grease-like material used to enhance heat transfer between two surfaces by filling in the microscopic voids caused by surface roughness. Most thermal greases, also known as Transistor Heat Sink Compound or Thermal Joint Compound, are made from silicone grease loaded with zinc oxide. Non-silicone based compounds are also available which in most cases are superior but more expensive than silicone-based alternatives.

THERMAL RESISTANCE (HEAT SINK): A measure of a heat sink's performance based on the temperature rise per unit of applied heat. The best heat sinks have the lowest thermal resistance.

THERMOELECTRIC DEVICE: A general and broad name for any thermoelectric apparatus. The term Thermoelectric Device has recently been modified to exclude thermoelectric modules in favour of thermoelectric assemblies.

THERMOELECTRIC GENERATOR: A device that directly converts energy into electrical energy based on the Seebeck Effect. Bismuth telluride-based thermoelectric generators have very low efficiencies (generally not exceeding two or three percent) but may provide useful electrical power in certain applications.

THERMOELECTRIC HEAT PUMP: Another name for a thermoelectric module or thermoelectric cooler. The term 'Heat Pump' has been used by some specifically to denote the use of a thermoelectric module in the heating mode.

THERMOELEMENT: Another name for a thermoelectric element or die.

THERMOPILE: When a thermoelectric module is used in a calorimeter application it is frequently called a thermopile. Some have used the word thermopile as a synonym for thermoelectric module regardless of application, but such use is unusual.

THOMSON EFFECT: The phenomena whereby a reversible evolution or absorption of heat occurs at opposite ends of a conductor having a thermal gradient when an electrical current passes through the conductor.

VISCOSITY: A fluid property related to the interaction between fluid molecules that determines the fluids resistance to sheering forces and flow.

11.2 Additional Tables

World Primary Energy Consumption (Btu), 1992-2001										
(Quadrillion (10^{15}) Btu)										
Region/Country	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
North America										
Canada	10.94	11.46	11.74	11.75	12.12	12.37	12.05	12.74	13.15	12.51
Mexico	5.12	5.13	5.30	5.31	5.55	5.65	5.93	6.06	6.19	6.00
United States	86.05	87.78	89.57	91.50	94.52	94.97	95.34	96.97	99.32	97.05
Other	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	**102.14**	**104.38**	**106.63**	**108.57**	**112.20**	**113.01**	**113.34**	**115.79**	**118.67**	**115.58**
Central & South America										
Argentina	2.12	2.29	2.25	2.33	2.41	2.50	2.63	2.64	2.68	2.66
Brazil	6.30	6.58	6.89	7.30	7.76	8.19	8.45	8.70	9.03	8.78
Chile	0.60	0.65	0.69	0.77	0.83	0.96	0.94	0.99	1.02	1.06
Colombia	0.98	1.07	1.10	1.10	1.19	1.23	1.24	1.19	1.20	1.13
Cuba	0.41	0.40	0.41	0.42	0.43	0.39	0.37	0.38	0.38	0.39
Venezuela	2.22	2.29	2.42	2.47	2.58	2.66	2.86	2.74	2.78	2.95
Other	2.70	2.83	3.00	3.16	3.30	3.45	3.60	3.72	3.90	3.93
Total	**15.33**	**16.11**	**16.77**	**17.54**	**18.50**	**19.38**	**20.11**	**20.36**	**20.99**	**20.92**
Western Europe										
Austria	1.19	1.23	1.23	1.28	1.29	1.33	1.35	1.44	1.42	1.42
Belgium	2.24	2.26	2.31	2.36	2.55	2.63	2.66	2.61	2.71	2.77
Denmark	0.82	0.85	0.84	0.88	0.88	0.91	0.90	0.88	0.89	0.90
Finland	1.18	1.20	1.23	1.12	1.14	1.26	1.29	1.30	1.30	1.33
France	9.41	9.37	9.28	9.54	9.92	9.87	10.18	10.28	10.36	10.52
Germany	14.00	14.06	14.01	14.32	14.30	14.30	14.33	14.12	14.18	14.35
Greece	1.04	1.09	1.11	1.12	1.15	1.22	1.29	1.28	1.35	1.39
Ireland	0.40	0.40	0.42	0.45	0.47	0.49	0.53	0.56	0.59	0.61
Italy	7.22	7.05	6.97	7.56	7.64	7.45	7.73	7.77	7.97	8.11
Netherlands	3.53	3.60	3.57	3.70	3.82	3.83	3.81	3.83	3.92	4.23
Norway	1.65	1.65	1.66	1.73	1.74	1.81	1.86	1.89	1.85	1.91
Portugal	0.76	0.78	0.81	0.85	0.88	0.94	0.99	1.01	1.08	1.09
Spain	4.12	4.04	4.22	4.48	4.39	4.72	5.02	5.21	5.48	5.70
Sweden	2.17	2.18	2.19	2.34	2.28	2.18	2.28	2.23	2.26	2.22
Switzerland	1.21	1.20	1.20	1.17	1.21	1.23	1.21	1.23	1.24	1.30
Turkey	2.13	2.33	2.23	2.47	2.74	2.96	3.02	2.92	3.01	2.89
United Kingdom	9.33	9.65	9.64	9.60	10.09	9.81	9.77	9.74	9.77	9.81
Croatia	0.33	0.33	0.36	0.37	0.37	0.38	0.40	0.38	0.42	0.43
Yugoslavia	0.69	0.55	0.60	0.46	0.70	0.73	0.77	0.64	0.62	0.63
Other	0.82	0.83	0.81	0.91	0.89	0.89	0.93	1.04	1.12	1.15
Total	**64.24**	**64.65**	**64.71**	**66.71**	**68.46**	**68.94**	**70.30**	**70.36**	**71.54**	**72.76**
Eastern Europe & Former U.S.S.R.										
Bulgaria	1.00	0.93	0.92	0.99	1.01	0.96	0.90	0.85	0.94	0.93
Former Czechoslovakia	3.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Czech Republic	0.00	1.66	1.56	1.68	1.78	1.71	1.57	1.47	1.53	1.53
Slovakia	0.00	0.79	0.77	0.82	0.81	0.80	0.79	0.77	0.75	0.83
Hungary	1.08	1.06	1.06	1.06	1.08	1.07	1.07	1.07	1.05	1.09
Poland	3.87	4.00	3.84	3.69	3.55	4.09	3.83	3.68	3.71	3.54
Romania	2.06	1.99	1.88	2.02	2.06	2.03	1.75	1.56	1.55	1.64

Azerbaijan	0.99	0.85	0.76	0.73	0.65	0.64	0.55	0.57	0.52	0.57
Belarus	1.57	1.34	1.10	1.06	1.07	1.07	1.07	1.12	1.29	1.21
Kazakhstan	3.37	2.79	2.25	2.04	1.99	1.70	1.64	1.63	1.63	1.73
Lithuania	0.44	0.37	0.36	0.37	0.33	0.34	0.36	0.30	0.32	0.33
Russia	34.88	32.67	29.63	28.24	27.92	25.52	25.63	26.69	27.40	28.20
Turkmenistan	0.29	0.27	0.27	0.29	0.28	0.29	0.25	0.31	0.39	0.48
Ukraine	8.88	8.58	7.31	7.21	6.73	6.44	6.26	6.33	6.14	6.08
Uzbekistan	1.66	2.04	1.76	1.85	1.91	1.89	1.84	1.87	1.94	2.08
Other	1.83	1.39	1.21	1.18	1.30	1.27	1.30	1.28	1.29	1.32
Total	**65.16**	**60.75**	**54.68**	**53.25**	**52.47**	**49.82**	**48.81**	**49.49**	**50.48**	**51.54**
Middle East										
Bahrain	0.24	0.29	0.28	0.29	0.29	0.35	0.36	0.36	0.38	0.39
Iran	3.35	3.47	3.66	3.81	3.96	4.44	4.64	4.94	5.05	5.18
Iraq	0.84	0.96	1.08	1.13	1.12	1.03	1.05	1.07	1.07	1.08
Israel	0.54	0.60	0.62	0.61	0.65	0.70	0.75	0.76	0.84	0.79
Kuwait	0.35	0.48	0.57	0.59	0.75	0.80	0.85	0.92	0.91	0.92
Oman	0.20	0.23	0.24	0.22	0.23	0.27	0.35	0.30	0.34	0.34
Qatar	0.46	0.53	0.54	0.54	0.55	0.58	0.59	0.56	0.61	0.64
Saudi Arabia	3.39	3.52	3.64	3.85	4.05	4.08	4.27	4.35	4.71	4.91
Syria	0.59	0.64	0.68	0.65	0.70	0.74	0.81	0.83	0.86	0.86
United Arab Emirates	1.55	1.48	1.49	1.60	1.67	1.79	1.84	1.80	1.80	2.06
Yemen	0.17	0.14	0.14	0.14	0.14	0.15	0.14	0.15	0.14	0.15
Other	0.36	0.39	0.45	0.47	0.49	0.52	0.54	0.56	0.57	0.58
Total	**12.03**	**12.73**	**13.37**	**13.93**	**14.61**	**15.44**	**16.19**	**16.61**	**17.28**	**17.92**
Africa										
Algeria	1.29	1.20	1.23	1.30	1.26	1.20	1.25	1.25	1.24	1.31
Angola	0.09	0.08	0.08	0.09	0.08	0.09	0.08	0.09	0.09	0.09
Egypt	1.43	1.51	1.55	1.58	1.73	1.79	1.85	1.89	2.02	2.13
Gabon	0.05	0.04	0.04	0.04	0.04	0.05	0.05	0.04	0.03	0.04
Libya	0.49	0.51	0.53	0.56	0.59	0.62	0.60	0.56	0.63	0.65
Morocco	0.33	0.36	0.40	0.37	0.40	0.40	0.42	0.44	0.46	0.48
Nigeria	0.78	0.80	0.74	0.83	0.85	0.85	0.81	0.81	0.81	0.92
South Africa	3.75	3.72	4.06	4.09	4.12	4.51	4.33	4.51	4.55	4.60
Zimbabwe	0.24	0.22	0.23	0.23	0.23	0.22	0.20	0.26	0.24	0.24
Other	1.48	1.51	1.56	1.55	1.61	1.66	1.70	1.75	1.87	1.99
Total	**9.92**	**9.96**	**10.43**	**10.64**	**10.91**	**11.40**	**11.30**	**11.61**	**11.95**	**12.45**
Asia & Oceania										
Australia	3.80	3.91	3.94	4.09	4.16	4.53	4.57	4.78	4.84	4.97
Bangladesh	0.29	0.31	0.34	0.37	0.39	0.40	0.42	0.47	0.50	0.51
Brunei	0.05	0.05	0.05	0.06	0.06	0.06	0.05	0.07	0.07	0.08
China	29.31	31.36	34.04	35.21	36.04	37.61	37.07	36.84	36.95	39.67
Hong Kong	0.52	0.56	0.61	0.66	0.68	0.61	0.69	0.83	0.79	0.87
India	8.71	9.10	9.59	11.10	11.17	11.47	11.76	12.16	12.67	12.80
Indonesia	2.54	2.87	3.05	3.25	3.51	3.64	3.48	3.86	4.05	4.63
Japan	19.14	19.41	20.18	20.83	21.48	21.78	21.43	21.57	21.75	21.92
Korea, North	3.02	3.12	3.08	3.04	2.97	2.82	2.72	2.71	2.85	2.84
Korea, South	4.79	5.55	6.01	6.63	6.95	7.41	6.82	7.32	7.89	8.06
Malaysia	1.14	1.29	1.43	1.47	1.64	1.67	1.68	1.74	1.87	2.27
New Zealand	0.74	0.77	0.80	0.86	0.82	0.81	0.79	0.80	0.86	0.84
Pakistan	1.29	1.41	1.50	1.58	1.70	1.68	1.73	1.78	1.86	1.87
Philippines	0.77	0.84	0.90	0.96	1.02	1.09	1.13	1.22	1.25	1.25

Singapore	0.97	1.08	1.16	1.18	1.35	1.49	1.54	1.55	1.57	1.65
Taiwan	2.21	2.43	2.66	2.93	3.19	3.21	3.48	3.64	3.99	4.07
Thailand	1.47	1.68	1.87	2.25	2.45	2.59	2.44	2.64	2.75	2.90
Vietnam	0.30	0.38	0.41	0.51	0.55	0.54	0.55	0.64	0.71	0.76
Other	0.55	0.58	0.63	0.64	0.64	0.66	0.68	0.72	0.75	0.79
Total	**81.60**	**86.71**	**92.25**	**97.61**	**100.77**	**104.05**	**103.04**	**105.36**	**107.98**	**112.76**
World Total	**350.43**	**355.28**	**358.84**	**368.25**	**377.93**	**382.04**	**383.09**	**389.58**	**398.88**	**403.92**

Table 11.1 World Energy Consumption taken from National Energy Center [1].

World Population, 1992-2001										
(Millions)										
Region/Country	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
North America										
Bermuda	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Canada	28.38	28.70	29.04	29.35	29.67	29.99	30.25	30.50	30.77	31.08
Greenland	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Mexico	87.11	88.74	90.39	91.99	93.57	95.13	96.65	98.13	100.25	101.75
Saint Pierre and Miquelon	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
United States	255.1	257.78	260.33	262.77	265.19	267.74	270.30	272.82	281.42	283.97
Total	**370.7**	**375.35**	**379.88**	**384.23**	**388.56**	**392.99**	**397.33**	**401.57**	**412.56**	**416.93**
Central & South America										
Antigua and Barbuda	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Argentina	33.42	33.87	34.32	34.77	35.22	35.67	36.12	36.58	37.03	37.52
Aruba	0.07	0.07	0.08	0.08	0.09	0.09	0.09	0.09	0.10	0.09
Bahamas, The	0.26	0.27	0.27	0.28	0.28	0.29	0.30	0.30	0.30	0.31
Barbados	0.26	0.26	0.26	0.26	0.26	0.26	0.27	0.27	0.27	0.27
Belize	0.20	0.21	0.21	0.22	0.22	0.23	0.24	0.24	0.25	0.23
Bolivia	6.90	7.07	7.24	7.41	7.59	7.77	7.95	8.14	8.33	8.47
Brazil	149.4	151.57	153.73	155.82	157.87	159.64	161.79	165.37	167.72	172.39
Cayman Islands	0.29	0.30	0.32	0.33	0.35	0.36	0.38	0.35	0.35	0.36
Chile	13.54	13.77	13.99	14.20	14.42	14.62	14.82	15.02	15.21	15.40
Colombia	36.41	37.13	37.85	38.54	39.30	40.06	40.83	41.59	42.32	42.80
Costa Rica	3.14	3.20	3.27	3.33	3.40	3.46	3.53	3.59	3.83	3.87
Cuba	10.83	10.90	10.95	10.98	11.02	11.07	11.12	11.14	11.18	11.22
Dominica	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Dominican Republic	7.47	7.62	7.77	7.83	7.97	8.10	8.21	8.32	8.40	8.53
Ecuador	10.74	10.98	11.22	11.46	11.70	11.94	12.17	12.41	12.65	12.88
El Salvador	5.43	5.52	5.64	5.73	5.82	5.91	6.03	6.15	6.28	6.40
Falkland Islands	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)
French Guiana	0.13	0.13	0.14	0.15	0.15	0.16	0.17	0.17	0.17	0.18
Grenada	0.09	0.09	0.09	0.09	0.10	0.09	0.09	0.09	0.09	0.09
Guadeloupe	0.41	0.41	0.42	0.42	0.43	0.44	0.44	0.44	0.44	0.44
Guatemala	9.22	9.47	9.72	9.98	10.24	10.52	10.80	11.09	11.39	11.68
Guyana	0.73	0.73	0.75	0.76	0.77	0.78	0.77	0.77	0.77	0.76
Haiti	6.76	6.90	7.04	7.18	7.34	7.49	7.65	7.80	7.96	8.13
Honduras	5.08	5.25	5.42	5.60	5.79	5.98	6.18	6.39	6.42	6.58
Jamaica	2.42	2.43	2.46	2.49	2.52	2.54	2.56	2.59	2.63	2.60
Martinique	0.38	0.39	0.39	0.39	0.40	0.40	0.41	0.41	0.42	0.42
Montserrat	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Netherlands Antilles	0.19	0.19	0.20	0.20	0.21	0.21	0.21	0.21	0.22	0.22
Nicaragua	4.13	4.26	4.40	4.43	4.55	4.67	4.80	4.94	5.07	5.21
Panama	2.49	2.53	2.58	2.63	2.67	2.72	2.76	2.79	2.82	2.86
Paraguay	4.45	4.57	4.70	4.83	4.96	5.09	5.22	5.36	5.50	5.64
Peru	22.45	22.74	23.13	23.53	23.95	24.37	24.80	25.23	25.66	26.35
Puerto Rico	3.58	3.62	3.65	3.69	3.73	3.77	3.81	3.92	3.94	3.96
Saint Kitts and Nevis	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Saint Lucia	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.16
Saint Vincent/Grenadines	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.12
Suriname	0.40	0.40	0.40	0.41	0.41	0.42	0.41	0.43	0.44	0.42
Trinidad and Tobago	1.24	1.25	1.25	1.26	1.26	1.27	1.28	1.29	1.29	1.30
Turks and Caicos Islands	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Uruguay	3.15	3.17	3.20	3.22	3.24	3.27	3.29	3.31	3.34	3.36
Venezuela	20.44	20.91	21.38	21.84	22.31	22.78	23.24	23.71	24.17	24.63
Virgin Islands, British	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Virgin Islands, U.S.	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12
Total	**366.6**	**372.76**	**379.02**	**384.93**	**391.13**	**397.05**	**403.33**	**411.11**	**417.58**	**426.20**
Western Europe										
Austria	7.91	7.99	8.03	8.05	8.06	8.07	8.08	8.09	8.10	8.08
Belgium	10.06	10.08	10.12	10.14	10.16	10.18	10.21	10.23	10.25	10.26
Denmark	5.17	5.19	5.20	5.23	5.26	5.28	5.30	5.33	5.34	5.33
Faroe Islands	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.05	0.05
Finland	5.04	5.07	5.09	5.11	5.12	5.14	5.15	5.17	5.18	5.19
France	57.37	57.65	57.90	58.14	58.37	58.61	58.85	59.10	58.89	59.19
Germany	80.57	81.19	81.42	81.66	81.90	82.06	82.02	82.09	82.18	82.36
Gibraltar	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Greece	10.32	10.38	10.43	10.45	10.48	10.50	10.52	10.55	10.58	10.60
Iceland	0.26	0.26	0.27	0.27	0.27	0.27	0.27	0.28	0.28	0.28
Ireland	3.55	3.57	3.59	3.60	3.63	3.66	3.70	3.75	3.79	3.84
Italy	56.86	57.05	57.20	57.30	57.40	57.52	57.59	57.65	57.76	57.95
Luxembourg	0.39	0.40	0.40	0.41	0.42	0.42	0.43	0.43	0.44	0.44
Malta	0.36	0.36	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.39
Netherlands	15.18	15.29	15.38	15.46	15.53	15.61	15.71	15.81	15.91	16.04
Norway	4.29	4.31	4.33	4.36	4.38	4.41	4.43	4.46	4.49	4.51
Portugal	9.86	9.88	9.90	9.92	9.93	9.94	9.97	9.98	10.01	10.02
Spain	39.01	39.09	39.15	39.21	39.27	39.32	39.37	39.42	39.47	40.27
Sweden	8.67	8.72	8.78	8.83	8.84	8.85	8.85	8.86	8.87	8.83
Switzerland	6.88	6.94	6.99	7.04	7.07	7.09	7.11	7.13	7.17	7.23
Turkey	57.93	58.51	59.71	60.61	61.53	62.46	63.39	64.34	67.38	68.61
United Kingdom	58.01	58.19	58.39	58.61	58.80	59.01	59.24	59.37	59.50	59.54
Bosnia and Herzegovina	4.41	4.28	4.22	4.18	4.17	3.70	3.80	3.84	3.98	4.07
Croatia	4.47	4.64	4.65	4.67	4.49	4.57	4.50	4.55	4.65	4.66
Macedonia, TFYR	2.06	2.07	1.95	1.97	1.98	2.00	2.01	2.00	2.00	2.00
Slovenia	2.00	1.99	1.99	1.99	1.99	1.99	1.98	1.99	1.99	1.99
Yugoslavia	10.45	10.48	10.52	10.55	10.58	10.60	10.62	10.64	10.66	10.67
Total	**461.2**	**463.66**	**466.05**	**468.20**	**470.07**	**471.71**	**473.55**	**475.52**	**479.33**	**482.42**
Eastern Europe & Former U.S.S.R.										
Albania	3.36	3.49	3.55	3.61	3.65	3.73	3.79	3.13	3.13	3.15
Bulgaria	8.54	8.47	8.44	8.41	8.36	8.31	8.26	8.21	7.95	7.87

Former Czechoslovakia	15.67	--	--	--	--	--	--	--	--	--
Czech Republic	--	10.33	10.34	10.33	10.32	10.30	10.29	10.28	10.27	10.29
Slovakia	--	5.32	5.35	5.36	5.37	5.38	5.39	5.40	5.40	5.40
Hungary	10.32	10.29	10.26	10.23	10.19	10.15	10.11	10.07	10.02	9.92
Poland	38.37	38.46	38.54	38.59	38.62	38.65	38.67	38.65	38.65	38.64
Romania	22.79	22.76	22.73	22.68	22.61	22.55	22.50	22.46	22.44	22.41
Armenia	3.69	3.73	3.75	3.76	3.77	3.79	3.79	3.80	3.80	3.46
Azerbaijan	7.38	7.49	7.60	7.68	7.76	7.84	7.91	7.98	8.05	8.11
Belarus	10.31	10.36	10.31	10.28	10.25	10.22	10.19	10.04	10.00	9.97
Estonia	1.54	1.52	1.50	1.48	1.47	1.46	1.43	1.41	1.39	1.38
Georgia	5.45	5.44	5.43	5.42	5.42	5.31	5.30	5.29	5.27	5.24
Kazakhstan	16.52	16.48	16.30	16.07	15.92	15.75	15.07	14.93	14.90	14.83
Kyrgyzstan	4.55	4.54	4.54	4.59	4.66	4.72	4.76	4.83	4.90	4.95
Latvia	2.63	2.59	2.55	2.51	2.49	2.47	2.45	2.43	2.43	2.36
Lithuania	3.74	3.73	3.72	3.71	3.71	3.71	3.70	3.66	3.70	3.49
Moldova	4.36	4.35	4.35	4.35	4.33	4.36	4.36	4.37	4.38	4.29
Russia	148.3	148.15	147.97	148.14	147.74	147.10	146.54	145.56	145.49	144.40
Tajikistan	5.57	5.64	5.74	5.84	5.92	6.05	6.16	6.28	6.41	6.54
Turkmenistan	4.03	4.31	4.41	4.51	4.57	4.64	4.70	4.76	4.82	4.88
Ukraine	52.06	52.24	52.11	51.73	51.33	50.89	50.50	50.11	49.57	49.11
Uzbekistan	21.21	21.70	22.19	22.56	23.01	23.56	24.05	24.76	25.16	25.56
Total	**390.4**	**391.39**	**391.68**	**391.84**	**391.47**	**390.94**	**389.92**	**388.41**	**388.13**	**386.25**
Middle East										
Bahrain	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.67	0.69	0.65
Cyprus	0.71	0.72	0.73	0.73	0.74	0.74	0.75	0.75	0.76	0.79
Iran	56.66	57.49	58.33	59.19	60.06	60.94	61.84	62.75	63.66	64.53
Iraq	18.31	18.89	19.47	20.04	20.62	21.18	21.75	22.34	22.95	23.58
Israel	5.12	5.26	5.40	5.54	5.70	5.83	5.97	6.10	6.29	6.45
Jordan	5.02	5.26	5.51	5.73	5.94	6.13	6.30	6.48	6.66	6.85
Kuwait	1.42	1.46	1.62	1.80	1.89	1.98	2.03	2.11	2.19	1.97
Lebanon	2.87	2.97	3.08	3.17	3.25	3.33	3.38	3.44	3.50	3.56
Oman	1.88	2.00	2.05	2.13	2.21	2.26	2.36	2.46	2.54	2.62
Qatar	0.53	0.56	0.59	0.61	0.62	0.63	0.64	0.66	0.67	0.70
Saudi Arabia	16.11	16.38	16.89	17.09	17.61	18.24	18.93	19.90	20.85	21.03
Syria	12.96	13.39	13.84	14.15	14.62	15.10	15.60	16.11	16.32	16.72
United Arab Emirates	2.16	2.10	2.29	2.31	2.44	2.62	2.78	2.94	2.61	2.65
Yemen	11.95	12.30	14.86	15.37	15.92	16.48	17.07	17.68	18.30	19.11
Total	**136.2**	**139.32**	**145.22**	**148.44**	**152.22**	**156.08**	**160.04**	**164.39**	**167.99**	**171.21**
Africa										
Algeria	26.27	26.89	27.50	28.06	28.57	29.05	29.51	29.95	30.99	31.84
Angola	10.61	10.80	10.97	11.34	11.70	12.05	12.40	12.76	13.13	13.53
Benin	4.92	5.08	5.24	5.41	5.59	5.64	5.82	5.99	6.17	6.42
Botswana	1.36	1.39	1.42	1.46	1.50	1.53	1.57	1.61	1.65	1.55
Burkina Faso	9.43	9.68	9.89	10.10	10.31	10.52	10.75	11.25	11.54	11.86
Burundi	5.74	5.81	5.87	5.93	6.02	6.11	6.20	6.30	6.40	6.50
Cameroon	12.18	12.52	12.87	13.28	13.56	14.30	14.44	14.69	14.88	15.20
Cape Verde	0.37	0.38	0.40	0.41	0.42	0.42	0.43	0.43	0.42	0.41
Central African Republic	3.08	3.15	3.22	3.29	3.35	3.41	3.56	3.65	3.72	3.78
Chad	5.96	6.10	6.21	6.74	6.95	7.17	7.40	7.64	7.89	8.14
Comoros	0.56	0.57	0.59	0.61	0.63	0.65	0.67	0.69	0.71	0.73

Congo (Brazzaville)	2.37	2.44	2.52	2.60	2.68	2.76	2.85	2.93	3.02	3.11
Congo (Kinshasa)	38.94	41.77	43.37	44.83	46.12	47.33	48.39	49.58	50.95	52.52
Cote d'Ivoire (Ivory Coast)	12.67	13.18	13.70	14.23	14.78	15.04	15.37	15.69	16.40	16.94
Djibouti	0.53	0.53	0.54	0.55	0.56	0.58	0.60	0.62	0.63	0.64
Egypt	54.08	55.20	56.34	57.51	58.76	60.08	61.34	62.65	63.98	67.89
Equatorial Guinea	0.37	0.38	0.39	0.40	0.41	0.42	0.43	0.44	0.46	0.47
Eritrea	--	--	3.22	3.32	3.43	3.59	3.71	3.90	4.30	4.47
Ethiopia	51.57	53.24	53.48	54.65	56.37	58.12	59.88	61.67	63.49	65.37
Gabon	0.99	1.02	1.05	1.08	1.11	1.14	1.15	1.18	1.21	1.24
Gambia, The	0.99	1.04	1.08	1.12	1.15	1.19	1.23	1.38	1.39	1.42
Ghana	16.00	16.44	16.88	17.30	17.71	18.10	18.49	18.89	19.41	19.73
Guinea	6.60	6.86	7.11	7.33	7.53	7.71	7.88	8.02	8.15	8.27
Guinea-Bissau	1.01	1.03	1.05	1.08	1.10	1.13	1.15	1.17	1.19	1.23
Kenya	26.98	28.11	29.29	30.52	31.80	28.41	29.34	30.03	30.67	31.29
Lesotho	1.76	1.79	1.83	1.87	1.97	2.01	2.06	2.10	2.14	2.19
Liberia	2.58	2.64	2.70	2.76	2.81	2.88	2.93	2.97	3.01	3.11
Libya	4.51	4.70	4.90	4.76	4.85	4.96	5.06	5.18	5.29	5.41
Madagascar	12.65	13.02	13.40	13.79	14.20	14.62	15.06	15.51	15.97	16.44
Malawi	8.82	9.13	9.46	9.79	10.14	10.44	10.74	11.03	11.31	11.40
Mali	9.22	9.45	9.68	9.93	10.19	10.46	10.74	11.04	11.35	11.50
Mauritania	2.10	2.15	2.21	2.28	2.35	2.42	2.50	2.58	2.67	2.75
Mauritius	1.08	1.10	1.11	1.12	1.13	1.15	1.16	1.17	1.19	1.20
Morocco	25.12	25.58	26.07	26.39	26.85	27.31	27.78	28.24	28.71	29.17
Mozambique	14.80	15.13	15.47	15.82	16.18	16.54	16.92	17.30	17.69	17.96
Namibia	1.47	1.50	1.55	1.59	1.62	1.66	1.69	1.72	1.76	1.79
Niger	8.23	8.36	8.81	9.11	9.43	9.75	10.10	10.46	10.83	11.23
Nigeria	91.13	93.79	96.51	99.21	102.10	104.96	107.88	110.85	115.22	116.93
Reunion	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.70	0.72	0.74
Rwanda	5.99	5.46	5.08	4.98	5.21	5.73	6.42	7.09	7.61	7.95
Saint Helena	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sao Tome and Principe	0.12	0.12	0.12	0.13	0.14	0.14	0.14	0.14	0.14	0.14
Senegal	7.70	7.91	8.13	8.57	8.80	9.04	9.28	9.40	9.52	9.66
Seychelles	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Sierra Leone	4.10	4.09	4.08	4.08	4.10	4.13	4.18	4.27	4.46	4.59
Somalia	8.86	8.95	9.08	9.25	9.00	8.82	8.50	8.20	7.96	7.75
South Africa	38.82	39.63	39.48	40.24	40.34	41.23	42.13	43.05	43.69	44.33
Sudan	27.32	28.13	28.45	28.75	29.17	29.48	29.79	30.42	31.10	31.81
Swaziland	0.83	0.85	0.88	0.91	0.94	0.97	0.99	1.01	1.03	1.04
Tanzania	25.99	26.73	27.49	28.28	29.09	29.98	33.46	34.29	35.12	35.97
Togo	3.73	3.84	3.93	4.06	4.17	4.28	4.40	4.51	4.53	4.66
Tunisia	8.48	8.66	8.81	8.96	9.09	9.21	9.33	9.46	9.56	9.67
Uganda	17.34	17.88	18.41	19.26	19.85	20.44	21.03	21.62	22.21	22.79
Western Sahara	0.25	0.26	0.27	0.28	0.28	0.28	0.29	0.28	0.27	0.26
Zambia	8.19	8.46	8.76	9.11	9.45	9.78	10.10	10.41	10.52	10.65
Zimbabwe	10.41	10.78	11.15	11.53	11.91	12.29	12.68	13.08	13.63	13.96
Total	**645.9**	**664.41**	**682.74**	**700.69**	**718.22**	**732.17**	**752.67**	**771.28**	**792.05**	**811.69**
Asia & Oceania										
Afghanistan	16.79	17.32	18.47	19.66	20.88	22.13	23.11	24.50	26.81	27.76
American Samoa	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07
Australia	17.49	17.67	17.85	18.07	18.31	18.52	18.73	18.97	19.16	19.49

Bangladesh	115.4	116.84	117.70	119.90	122.10	124.30	131.80	134.58	137.44	140.37
Bhutan	1.58	1.60	1.61	1.64	1.81	1.86	2.00	2.06	2.09	2.15
Brunei	0.27	0.28	0.28	0.29	0.30	0.31	0.31	0.34	0.34	0.35
Burma	42.33	43.12	43.92	44.35	45.08	45.78	46.46	47.11	47.75	48.36
Cambodia	9.06	9.31	9.87	10.20	10.34	10.37	12.34	12.66	12.99	13.31
China	1,183.60	1,196.40	1,208.80	1,220.52	1,232.46	1,242.80	1,253.90	1,264.80	1,275.10	1,285.00
Cook Islands	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fiji	0.75	0.77	0.78	0.80	0.78	0.79	0.80	0.81	0.81	0.83
French Polynesia	0.21	0.21	0.21	0.22	0.22	0.23	0.23	0.25	0.25	0.26
Guam	0.14	0.14	0.15	0.15	0.15	0.16	0.15	0.15	0.16	0.16
Hong Kong	5.80	5.90	6.04	6.16	6.44	6.49	6.54	6.61	6.67	6.72
India	868.9	886.25	903.94	921.99	939.54	955.22	970.93	986.61	1,002.14	1,017.54
Indonesia	186.1	189.13	192.22	195.28	198.34	201.39	204.42	207.44	210.49	214.84
Japan	124.4	124.83	125.18	125.47	125.76	126.07	126.41	126.65	126.87	127.34
Kiribati	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09
Korea, North	21.15	21.51	21.87	22.24	22.61	22.88	22.98	22.69	22.45	22.30
Korea, South	43.75	44.19	44.64	45.09	45.54	45.99	46.43	46.86	47.27	47.34
Laos	4.35	4.46	4.57	4.69	4.80	4.92	5.03	5.16	5.28	5.40
Macau	0.37	0.38	0.40	0.41	0.42	0.42	0.43	0.43	0.44	0.45
Malaysia	19.04	19.56	20.11	20.67	21.17	21.66	22.18	22.71	23.27	23.63
Maldives	0.23	0.24	0.25	0.25	0.26	0.27	0.27	0.28	0.27	0.28
Mongolia	2.20	2.23	2.27	2.30	2.27	2.30	2.33	2.36	2.39	2.42
Nauru	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Nepal	19.06	19.39	19.86	20.34	20.83	21.33	21.84	22.37	22.90	23.59
New Caledonia	0.18	0.18	0.19	0.19	0.20	0.20	0.20	0.20	0.20	0.20
New Zealand	3.51	3.55	3.60	3.66	3.71	3.76	3.79	3.81	3.83	3.85
Niue	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)
Pakistan	119.23	122.79	126.47	130.25	134.15	138.16	139.58	141.51	143.50	144.97
Papua New Guinea	3.85	3.92	4.00	4.07	4.40	4.50	4.60	4.70	4.81	4.92
Philippines	65.34	66.98	68.62	70.27	71.90	73.53	74.15	74.75	76.32	77.13
Samoa	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07
Singapore	3.23	3.32	3.42	3.53	3.67	3.79	3.92	3.95	4.02	4.13
Solomon Islands	0.34	0.35	0.37	0.38	0.39	0.40	0.42	0.43	0.45	0.46
Sri Lanka	17.43	17.65	17.89	18.14	18.32	18.55	18.77	19.04	19.36	19.50
Taiwan	20.80	21.00	21.18	21.36	21.53	21.74	21.93	22.09	22.28	22.41
Thailand	57.29	58.01	58.72	59.40	60.00	60.60	61.16	61.56	62.32	62.91
Tonga	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
US Pacific Islands	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Vanuatu	0.15	0.16	0.16	0.17	0.17	0.18	0.18	0.19	0.20	0.20
Vietnam	69.41	71.03	72.51	73.96	74.36	75.08	76.11	77.12	77.69	79.18
Total	**3,044.03**	**3,091.00**	**3,138.45**	**3,186.42**	**3,233.56**	**3,277.03**	**3,324.78**	**3,366.13**	**3,408.71**	**3,450.11**
World Total	**5,414.96**	**5,497.88**	**5,583.04**	**5,664.75**	**5,745.22**	**5,817.97**	**5,901.62**	**5,978.41**	**6,066.34**	**6,144.81**

Table 11.2 World Population, taken from National Energy Center [11].

Beaufort Number	Description of wind	Observations	Limit of wind speed /m.s^{-1}
0	Calm	Smoke rises vertically	Less than 0.5
1	Light air	Direction of wind shown by smoke drift but not by wind vanes	0.5 to 1.5
2	Light breeze	Wind felt on face; leaves rustle; ordinary vane moved by wind	1.5 to 3.0
3	Gentle breeze	Leaves and small twigs in constant motion; wind extends light flag	3 to 6
4	Moderate breeze	Raises dust and loose paper; small branches are moved	6 to 8
5	Fresh breeze	Small trees in leaf begin to sway	8 to 11
6	Strong breeze	Large branches in motion; umbrellas used with difficulty	11 to 14
7	Moderate gale	Whole trees in motion; inconvenience felt when walking into wind	14 to 17
8	Fresh gale	Twigs broken off trees; generally impedes progress	17 to 21
9	Strong gale	Slight structural damage occurs (slates and chimney pots removed from roofs)	21 to 24
10	Whole gale	Seldom experienced inland; trees uprooted; considerable structural damage occurs	24 to 28
11	Storm	Very rarely experienced; accompanied by widespread damage	28 to 32
12	Hurricane	(Yacht crews take up golf)	32 to 36

Table 11.3 The Beaufort scale

11.3 Body Cellar Metabolism

There are two primary sources of energy for endergonic reactions. These are the exergonic reactions:

$ATP + H_2O \rightarrow ADP + P$	$\Delta G = -7.3$ kcal / mol
$NADH + H^+ + 1/2\ O_2 \rightarrow NAD^+ + H_2O$	$\Delta G = -52.4$ kcal / mol

The negative signs indicate the reactants lose energy and therefore the reactions are exergonic. ATP (adenosine tri-phosphate) is used throughout the body to store energy that would otherwise be released as heat. Similarly, the 'reduction' (gain of one or more electrons by a molecule, raising its internal energy) reaction for nicotinamide adenine dinucleotide (NAD)

$$NAD^+ + H_2 \rightarrow NADH + H^+$$

stores energy which is released by the "oxidation" (loss of an electron, freeing energy) of NADH. Living organisms also use the reduction of flavin adenine dinucleotide

$$FAD + H_2O \rightarrow FADH_2 + 1/2\ O_2,$$

which stores 45.9 kcal / mol of energy. Its associated oxidation reaction,

$$FADH_2 + 1/2\ O_2 \rightarrow FAD + H_2O$$

releases it. Assuming that there is plenty of water, ADP, NAD^+, FAD and hydrogen ions available in the cell, and will leave those reactants out of the reactions below.

In cellular respiration, the "burning" of glucose with oxygen produce carbon dioxide and water in the model of metabolism:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O,$$

From the '$\Delta_f H$' of the products and the reactants, '$\Delta_r H$' can be found from Hess Law. The amount of glucose can be determined and that will produce the amount of heat in the body:

$$mass_{glucose} = (\Sigma_i Q_i \times 180 \text{ g/mol}_{glucose}) / \Delta_r H_{mass\ glucose} \qquad (11.1)$$

This reaction takes place inorganically, and essentially all of the energy released is entropic heat. Cellular respiration breaks the process up into myriad steps involving small changes in energy, and therefore small releases of entropy. The steps are reversible, given sufficient variations in concentrations, and so the overall process gains a great deal in efficiency.

List are the four major parts of cellular respiration. Water is necessary to supply hydrogen ions and oxygen for these processes; it is also a product of many of them. It is however left out of most equations to make the counting easier.

1. Glycolysis:

   glucose + 2NAD + 2ADP → 2 pyruvate + 2NADH + 2ATP

   (ΔG of complete aerobic oxidation of pyruvate is -273 kcal / mol)

   Glycolysis is very efficient because most of the reactions involved take place under nearly reversible conditions.

2. Intermediate step:

   Pyruvate + NAD → AcetylCoA + NADH + CO_2

   (assume $\Delta G = 0$)

3. TriCarboxylic Acid (TCA) Cycle:

   AcetylCoA → 3NADH + $FADH_2$ + ATP + $2CO_2$

4. Electron Transport:

   $NADH + H^+ + 1/2\ O_2 \rightarrow NAD^+ + 3ATP$

   $FADH_2 + 1/2\ O_2 \rightarrow FAD + 3H_2O + 2ATP$

   This is a nearly reversible series of oxidations to O_2; this pathway includes the:

5. Proton pump: oxidation is used to increase the proton concentration in mitochondria; that gradient is used to drive the generation of ATP. The proton potential is the sum of the membrane potential and the concentration gradient

$$\Delta V = 0.16V + k\,T \ln (H^{+}_{out} / H^{+}_{in}) / e \qquad (11.12)$$

(note that $\log_{10}(H^{+}) = -pH$, and pHin - pHout = 1). Therefore 2 protons provide enough energy to generate one ATP.

To summarize aerobic cellular respiration; for "eukaryotic" cells (those with nuclei, as in the case of human beings), 2 ATP are used to transport cytoplasmic NADH to the mitochondria, so the final reaction is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 36ATP.$$

The change in free energy for this reaction is - 423.2 kcal / mol; the associated entropy generated is 1.36 kcal / mol K, and the efficiency is approximate 38 %. This is a relatively efficient process for biological systems and even correspondent to the efficiency of a motorcar

11.4 Pollutants

Before identifying methods to reduce and control various types of pollution, it is important to recognize exactly what these pollutants are and how they formed. Understanding how pollution is created is a first step in developing techniques to combat it.

11.4.1 Carbon Dioxide

As the best known of the greenhouse gases, carbon dioxide is under constant scientific scrutiny and is the focus of social and political concern. Produced by the process of combustion, particularly the burning of fossil fuels such as coal, oil and natural gas, $C0_2$ is emitted in gaseous form in the flue gases originating from any combustion device.

$C + 0_2 = C0_2$ (Burning of carbon based fuels)
$CH_4 + 20_2 = C0_2 + 2H_20$ (Burning of gas)

Carbon dioxide molecules, unlike other components of pure air have the property of absorbing the infra-red (heat) radiation of the sun. Therefore, the more C02 in the atmosphere, the more heat the atmosphere canabsorb which could contribute to the melting of the polar ice caps. The objective of an efficient burner is to achieve combustion conditions as near to the stoichiometric parameter of the fuel as possible. The term stoichiometric literally means "measurement of elements" and is used to denote a condition where the equivalent weights of substances in a chemical reaction have been precisely determined. At near stoichiometric level, the oxygen content of the flue gas is at the lowest percentage and the $C0_2$ is at the highest. However, the more efficient the burner, the lower the amount of excess air used in the combustion process resulting in the least volumetric emission of $C0_2$ in the flue gases. Perfect combustion involves using exact weights of air and fuel, although in practice this is not possible. Even the most superior burner unit will use a certain amount of excess air although

11.4.2 Sulphur Oxides

Closely associated with major air pollution disasters, sulphur oxides have long been responsible for considerable environmental damage. However, as these pollutants are generally the product of the fuel, sophisticated combustion techniques will not have any effect on its formation. As probably the most significant single air pollutant, $S0_2$ is produced when sulphur or fuels containing sulphur are burned:

$$S+0_2 = S0_2$$

$S0_3$ is created in the atmosphere by the oxidation of $S0_2$ under the influence of sunlight:

$$2S0_2+0_2 = 2S0_3$$

Additionally, some $S0_3$ is introduced directly from combustion processes along $S0_2$. The moisture in the air reacts rapidly with SO_3 to form a sulphuric acid:

$$S0_3+H_2O = H_2SO_4$$

When such conversions occur the material originally introduced to the atmosphere is called a primary air pollutant. The new materials produced by chemical reaction in the air are called Secondary air pollutants.

11.4.3 Carbon Monoxide

CO usually formed when there is a lack of oxygen in the combustion process or when a flame is 'chilled'. This gas can prove fatal if inhaled.

11.4.4 Nitrogen Oxides

NO_x is the collective term for nitrogen oxide gases created during the high temperature combustion, expressed chemically as:

NO (Nitric Oxide) + $N0_2$ (Nitrogen Oxide)

The formation of NO_x is a complex process which takes place in the pre-combustion, combustion and post-flame regions. It involves the reactive combination of nitrogen found within the combustion air and natural or organically bound nitrogen within the fuel itself. Attempts have been made to identify different NO_x formation mechanisms NO_x can be produced in isolated sections of the flame for over 80% of the combined NO_x to be produced in only 10% of the flame volume.

NO_x is a thermally produced gas and therefore its reduction is largely dependant on the control of flame temperature.

11.4.5 Smoke

Excess fuel, incomplete combustion and flame impingement will result in the formation of smoke which discharges particles of carbon into the atmosphere and also causes fouling of the boiler surfaces which will impair efficiency.

11.4.6 Noise

Damaged hearing and stress related conditions are the results of another form of pollution. Defined simply as "unwanted sound" the effects of noise can range from mild annoyance to permanent hearing loss. In addition to this, noise can also disrupt working efficiency through inducing stress.

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