INVESTIGATION OF USABLE THERMOELECTRIC VOLTAGE GENERATED BY COMPUTER WASTE HEAT

AMOLLO TABITHA AWUOR

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been submitted in part or whole for an award in any other university.

Amollo Tabitha Awuor
SM13/2811/10
Signature:____________________________ Date________________

Recommendation

This thesis has been submitted for examination with our approval as university supervisors.

Dr. M. S. K. Kirui
Egerton University
Signature:____________________________ Date________________

Dr. Hussein S. A. Golicha
Egerton University
Signature: ____________________________ Date________________

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ABSTRACT

Computers use electric current to process information. Heat is generated in computer components whenever current flows through it, the heat generation causes unavoidable heat build up and a subsequent temperature rise at and around the components. High operating temperature is dangerous to the safety and reliability of components since the failure rate of computer components increases almost exponentially with the increase in operating temperatures. Similarly, the heat generation leads to wastage of energy yet there exist energy crisis in the world. Computer industries are building smaller and denser circuits to improve the computing power and portability. The main drawback of this miniaturization is the increase in the amount of heat produced per unit area of the component, so huge amount of money in the semiconductor industry is put towards thermal management. This study sought to determine the heat generated in a computer, the usable thermoelectric power that can be generated from computer waste heat and the reliability of using the generated thermoelectric energy to power the computer. Compaq P4, Compaq P3 and Dell P4 desktop computers were used for the study. The heat generation of the desktop computers under varying processor workloads was found by measuring the current and voltage from the PSU to the motherboard and HDD of the computers using a digital multimeter. Type J thermocouples were connected at the heat generation modules of the computers to convert waste heat in the desktop computers to thermoelectric energy. 2286/2285 data logger was used to make the measurements of temperature and the corresponding thermoelectric voltage generated from the thermocouples. These measurements were taken at room temperature. Compaq P4, Dell P4 and Compaq P3 generated heat at the rate of 286.33, 152.57 and 182.37 joules per second respectively. An optimum thermoelectric voltage of 11.583 μV, 9.889 μV and 7.269 μV was generated from the waste heat of Compaq P4, Dell P4 and Compaq P3 desktop computers respectively using thermocouples. Computers produce heat from which usable thermoelectric energy can be generated hence the heat produced by computers should be converted to thermoelectric energy.

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LIST OF ABBREVIATIONS

CRT	Cathode ray tube
GPS	Global Positioning System
IHS	Integrated Heat Spreader
PSU	Power Supply Unit
TEG	Thermoelectric Generator
VLC	Video LAN Client

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Computer components depend on the passage of electric current to process information. When a current I flows through a component of resistance R, heat of magnitude I^2R is generated. This causes a heat build up and a subsequent temperature rise at and around the component (Çengel, 1998). The temperature of the component will thus rise leading to the destruction of the component unless heat is transferred away from it. However, the temperature of the component remains constant when the rate of heat removal equals the rate of heat generation (Olin, 2010). Multimedia data processed through Boolean calculation are growing and the corresponding processing speed is increasing which results in high operation temperatures of the equipment and IC modules in the computer (Cheng-Ping, 2007).

The computer components which produce heat and are susceptible to performance loss and damage due to the heating are integrated circuits. Research shows that, increasing (for example) hard disk drive temperature by 5°C has the same effect on reliability as switching from 10% to100% hard disk drive workload and that each one degree drop in the operating temperature is equivalent to a 10% increase of their service life (Karabuto, 2005). The amount of heat generated by an integrated circuit, the prime cause of heat build up in modern computers is a function of the efficiency of the integrated circuit design, the technology used in its construction and the frequency and voltage at which it operates (Mudawar, 2001).

Any matter whose temperature is above absolute zero continuously emits thermal radiation which includes the entire visible and infrared radiation (IR) as well as a portion of the ultraviolet (UV) radiation. As the temperature of the computer component rises, the component emits energy in form of thermal radiation. This energy emitted per unit time and per unit surface area is given by $E = \sigma T^4$ where σ is the Stefan-Boltzmann constant and T is the absolute temperature of the surface of the components (Das, 2006; Dutta, 2006).

There are two ways which are employed to keep the temperature of each component at a safe level namely; peripheral and integral means. With regard to integral means, CPUs are designed with energy efficiency, though improved efficiency may only allow increased performance instead of reduced heat. Peripheral means of keeping the temperature of each component at safe level include; heat sinks to increase the surface area which dissipates heat, fans to speed up the exchange of air heated by the computer parts for cooler ambient air and in some cases soft cooling; the throttling of computer parts in order to decrease heat (Mudawar and Sund, 2008).

1.2 Statement of the Problem

Heat is generated in a computer component when current flows through it. The generation of heat and the associated rise in temperatures are unavoidable byproducts of the operation of the computer system. Miniaturization (to increase portability) and improvement of computing power of computer systems is limited by heat generation as miniaturization increases the heat generated per unit area of the components. Computers could actually run much faster but are not allowed to because of the heat build up, so huge amount of money in the semiconductor industry is put towards thermal management. Also, there exist energy crisis in the world and consequently various measures have been taken to combat the crisis. One of the useful measures is to avoid wastage of energy in any of its form. Therefore, there is need to determine the amount of heat dissipated in a computer, tap the waste heat and convert it to electrical voltage which is usable by the computer and establish whether it can be a reliable source of electrical energy to power the computer or its peripherals.

1.3 Objectives

1.3.1 Main Objective

To study the reliability of reusing the waste heat from a desktop computer to generate thermoelectric voltage that can power the desktop computer.

1.3.2 Specific Objectives

i. To determine the amount of heat generated in a desktop computer under varying processor workload.
ii. To determine the optimum thermoelectric voltage that can be generated from the waste heat of the desktop computer.
iii. To determine the reliability of the usage of the generated thermoelectric voltage to power the desktop computer.

1.4 Hypotheses

i. That the heat generated in a desktop computer does not vary with change in processor workload.
ii. That the optimum amount of thermoelectric voltage that can be generated from the waste heat in a desktop computer is negligible.
iii. That the thermoelectric voltage generated from the waste heat is not reliable to power the computer.

1.5 Justification

Heat accounts for a tremendous amount of wasted energy in electronics. The generation of heat and the associated elevation of temperatures are unavoidable byproducts of the operation of every electronic system including a computer. Continuous increase in the components temperature would lead to its destruction unless the heat is transferred away. Reliability and durability of the integrated circuits such as CPU, chipsets, graphics cards and hard disk drives depend much on their operating temperatures. Computer industries are building smaller and denser circuits, but their main limiting factor is to increase computing power without producing more heat. This study aims at determining the heat generated in a computer and converting the waste heat thereof to electrical voltage usable by the computer; this would solve the computer industry’s problem of increasing computing power without increasing the operating temperature. This would also decrease the power requirements of the computer since power saving in modern computers is an issue of primary concern as fuel prices continue to skyrocket.

1.6 The Scope and Limitations

The research work was carried out from October 2011 to January 2012 in the physics laboratory in Maseno University. Dell desktop computer (P4:2.8GHZ, RAM: 5.2MB, HDD: 40GB), Compaq desktop computer (P3:976MHZ, RAM: 256MB, HDD: 20GB), Compaq desktop computer (P4:2.0 dual core processor, RAM: 2GB, HDD: 250GB), Compaq CRT monitor, digital thermometer, digital multimeter, a resistance box, six type J thermocouples (iron-constantan) and 2286/2285 data logger were used for the study. The voltage, current, temperature and thermoelectric voltage generated were measured at room temperature. It was risky taking the measurements with the computers in operation especially with the heat sinks of the computers off, extreme care had to be taken to ensure the computer components do not blow.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Computer components use electric current to perform their duties and they are potential sites for excessive heating. A typical desktop personal computer consists of circuit boards plugged into a motherboard which contains the microprocessor and the memory chips as well as the network of interconnections enclosed in a formed sheet metal chassis, which also contains the hard disk and CD_ROM drives connected to this “magic” box are the monitor, a keyboard, a printer and other auxiliary equipment (Çengel, 1998). The computer components which produce a lot of heat and are susceptible to performance loss and damage due to heating are integrated circuits which are on the motherboard and hard drives (Karabuto, 2005). The amount of heat given off by a computer depends on type and speed of the CPU, type, size and efficiency of the CPU cooler, cleanliness of the CPU cooler, the number of PC cards installed, the type of PC cards installed, case design and number/ type of case fans fitted, the processes the CPU is running, the type of graphic cards makes and the design of the motherboard (Sergei, 2010).

Demand for higher computational power has forced hardware designers to plan processor heat dissipation carefully. An obvious approach to the problem of heat dissipation is to decrease the power required for high end CPUs through higher integration, optimized instruction sets and more exotic techniques such as “reversible computation”. In addition, the explosion of mobile peripherals, such as wireless internet radios, video cameras, sound cards, body network, scanners and global positioning system (GPS) units creates an even higher load as functionality increases (Maguire and Starner, 1998).

2.2 Effects of Heat Dissipation on Computer Components

Individual computer components do not wear out with time as they have no moving parts, therefore they are inherently reliable and they can operate safely for many years if the components operate at room temperature. But computer components are observed to fail under prolonged use at high temperatures. This failure is caused by high thermal stresses in the soldier joints of the computer components mounted on circuit boards resulting from temperature variations. Other possible causes of failure are diffusion in semiconductor materials, chemical reaction and creep in the bonding materials, among other things (Çengel, 1998). Hence the failure rate of computer components increases exponentially with the operating temperature as shown in figure 1.

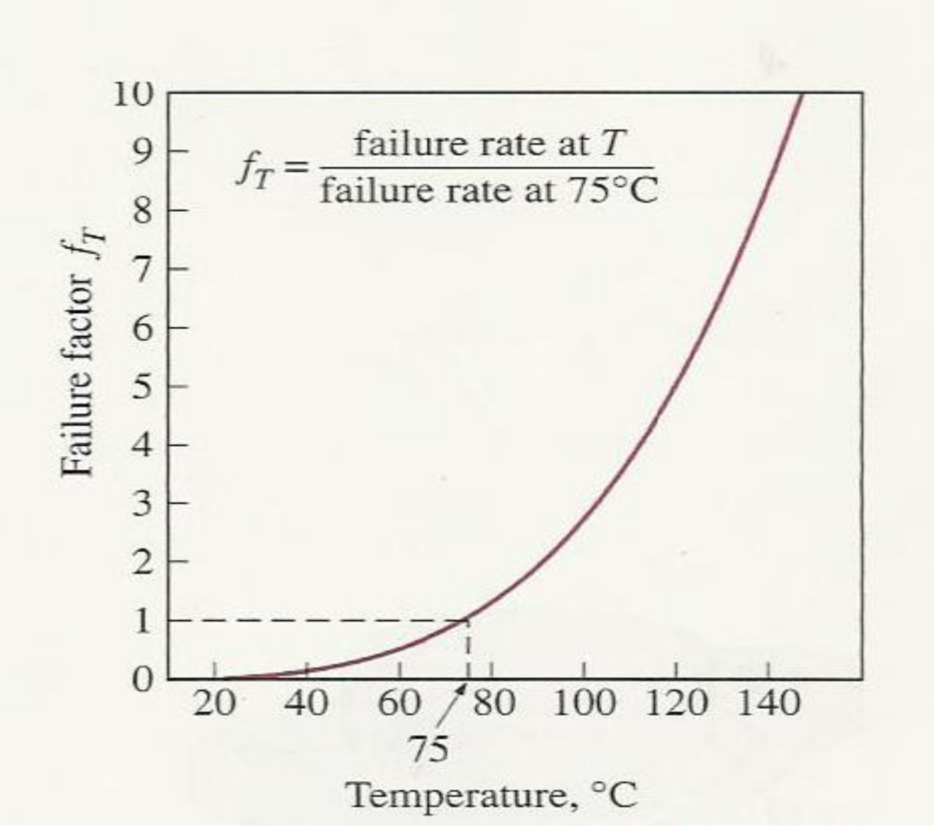

Figure1: A graph of failure factor f_T against temperature T of bipolar digital devices (Çengel, 1998).

The cooler the electronic device operates, the more reliable it is. A rule of thumb is that the failure rate of electronic component is halved for each 10°C reduction in their junction temperature (Çengel, 1998).

2.3 Cooling Desktop Personal Computers

Cooling techniques used in desktop computers include air cooling, liquid cooling, heat pipe, conduction and radiation cooling, integrated chip cooling techniques.

2.3.1 Air Cooling

Desktop computers typically use one or more fans for cooling. Most manufacturers recommend bringing cool, fresh air in at the bottom front of the case and exhausting warm air from the top rear. If there is more air being forced into the system than is being pumped out, this is referred to as “a positive” air flow, as the pressure inside the unit would be higher than outside. A balanced or neutral airflow is the most efficient although a slightly positive airflow results in less dust build up if filters are used (Olin, 2010).

2.3.2 Liquid Cooling and Heat Pipes

Liquid cooling systems can be classified as direct cooling and indirect cooling systems. In direct cooling system, the electronic components are in direct contact with the liquid whereas in indirect cooling systems there is no direct contact with the components (Olin, 2010). Personal computers that are cooled in this manner do not generally require any fan or pumps, and maybe cooled exclusively by passive heat exchange between the computer parts, the cooling fluid and the ambient air. The liquid used must have sufficiently low electrical conductivity in order for it not to interfere with the normal operation of the computer components. Water cooling has comparatively low noise level which compares favorably to that of active cooling which can become quite noisy. One disadvantage to water cooling is the potential for a coolant leak which can damage any electronic component that comes in contact with it, another drawback to water cooling is the complexity of the system; an active heat sink is much simpler to build, install, and maintain than a water cooling solution (Murphy, 2007). A heat pipe is a hollow tube containing a heat transfer liquid. As the liquid evaporates, it carries heat to the cool end where it condenses and then returns to the hot end. Heat pipes thus have a much higher effective thermal conductivity than solid materials. The heat sink on the CPU is attached to a larger radiator heat sink. Both heat sinks are hollow as in the attachment between them, creating one large heat pipe that transfers heat from the CPU to the radiator which is then cooled using a fan. Because of the efficiency of this method of cooling, many desktop CPUs as well as high end chipsets use heat pipes in addition to active fan-based cooling to remain within safe operating temperatures (Sergei, 2010). The type of fluid and the operating pressure inside the heat pipe depends on the operating temperature of the heat pipe (Mudawar and Sund, 2008). The heat removal capacity of various heat pipes (classified according to dimensions) are given in table 1.

Table 2.1: Heat removal capacity of various heat pipes

Outside diameter (cm)	Length (cm)	Heat removal rate (watts)
0.635	15.2 30.5 45.7	300 175 150
0.95	15.2 30.5 45.7	500 375 350
1.27	15.2 30.5 45.7	700 575 550

(Çengel, 1998)

2.3.3 Conductive and Radiative cooling

Conductive and radiative cooling can be classified as passive heat sink cooling and active heat sink cooling. Passive heat sink cooling involves attaching a block of machined or extruded metal to the component that it is protecting (usually an IC or CPU). Usually a heat-sink is attached to the integrated heat spreader (IHS), essentially a large flat plate attached to the CPU, with conduction paste layered between. This dissipates or spreads the heat locally. Unlike a heat sink, a spread is meant to redistribute heat, not to remove it. Passive heat sinks are commonly found on parts that do not get very hot. Dust build up between the metal fins of a heat sink gradually reduces efficiency but can be countered with a gas duster by blowing away the dust along with other unwanted excess materials (Mudawar, 2001). Active heat sink uses the same principle as passive heat sink, with the addition of a fan that blows air over or through the heat sink. The air movement increases the rate at which the heat sink can exchange heat with the ambient air. Active heat sinks are the primary method of cooling modern processors and graphic cards.

2.3.4 Integrated Chip Cooling Techniques.

Currently there are two techniques namely; micro-channel heat sinks and jet impingement cooling. In micro channel heat sinks, channels are fabricated into the silicon chip (CPU) and a coolant is pumped through them. The channels are designed with very large surface area which results in large heat transfers. Heat dissipation of 3000W/cm^2 has been reported with this technique (Bowers and Mudawar, 1994), this is quite a lot compared with the sun power density of around 7400 W/cm^2.The heat dissipation can be increased further if two phase flow cooling is applied. Unfortunately the system requires large pressure drops, due to the small channels, and the heat flux is lower with dielectric coolants. In jet impingement cooling a coolant is flown through a small surface to form a jet. The jet is directed towards the surface of the CPU chip and can effectively remove large heat fluxes.

2.4 Thermal Radiation

This is a type of electromagnetic radiation which is pertinent to heat transfer. It's emitted as a result of vibration and rotational motions of molecules, atoms and electrons of a substance. Temperature is a measure of the strength of these activities at the microscopic level, and the rate of thermal radiation emission increase with increase in temperature. Thermal radiation is continuously emitted by all matter whose temperature is above absolute zero (Das, 2006). Thermal radiation also, is the portion of the electromagnetic spectrum that extends from about 0.1 to 100µm since the radiation emitted by bodies because of their temperature falls almost entirely into this wavelength range. Thus thermal radiation includes the entire visible and infrared (IR) radiation as well as a portion of the ultraviolet (UV) radiation. The radiation emitted by bodies at room temperature falls in the infrared region of the spectrum (Dutta, 2006). Heat dissipation in the computer components causes a heat build up and a subsequent temperature rise at and around the component thus the computer emits thermal radiation as their temperature rises. Heat transfer in computer components occurs simultaneously by conduction (heat sink), convection (fan) and radiation (Çengel, 1998). For conduction and convection the heat transfer between two locations depends on the temperature difference of the locations to approximately the first power and a physical medium must be present to carry the energy with the convective flow or to transport it by means of thermal conduction. The transfer of energy by thermal radiation between two bodies depends on the difference of the individual absolute temperature of the bodies each raised to a power in the range of about four or five and no medium need to be present between to locations for radiant interchange to occur. Radiation energy will pass perfectly through a vacuum (Howell and Siegel, 1981).

2.5 Thermoelectric Effect

The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice versa. A thermoelectric device creates a voltage when there is a difference in temperature on each side. Conversely, when a voltage is applied to it, it creates a temperature difference (Ellis and Winder, 1996). At the atomic scale, an applied temperature gradient causes charged carriers in the material to diffuse from the hot side to the cold side, hence inducing a thermal current. The term "thermoelectric effect" encompasses three separately identified effects, the Seebeck effect, Peltier effect and Thomson effect which are thermodynamically reversible (Long, 2001).

2.5.1 Seebeck Effect

The Seebeck effect is the conversion of temperature differences directly into electricity. The voltage created by this effect is on the order of several microvolts per Kelvin difference (Chen, *et al.,* 2009). For example, copper-constantan has a Seebeck coefficient of 41 microvolt per Kelvin at room temperature. The voltage V developed can be derived from;

$$V = \int_{T1}^{T2} S_B(T) - S_A(T)\, dT \quad \ldots\ldots \quad (2.01)$$

Where S_A and S_B are the thermo powers or Seebeck coefficient of metals A and B as a function of temperature and T_1 and T_2 are the temperatures of the two junctions. The Seebeck coefficients are non-linear as a function of temperature and depend on the conductor's absolute temperature, material and molecular structure. If the Seebeck coefficients are effectively constant for the measured temperature range, equation 2.01 can be approximated as (Ferreira and Kim, 2008);

$$V = (S_B - S_A) \cdot (T_2 - T_1) \quad \ldots\ldots \quad (2.02)$$

The thermo power or Seebeck coefficient, denoted by S of a material is the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material and the entropy per charge carrier in the material. S has units of V/K, though $\mu V/K$ is more common. An applied temperature difference causes charge carriers in the material to diffuse from the hot side to the cold side, leaving behind their oppositely charged and nuclear at the hot side thus giving rise to a thermoelectric voltage (Majumdar, 2004). Since a separation of charges creates an electric potential, the buildup of charged carriers onto the cold side eventually ceases at some maximum value since the electric field is at equilibrium. An increase in the temperature difference resumes a buildup of carriers on the cold side leading to an increase in the thermoelectric voltage and vice versa (Disalvo, 1999). The materials temperature and crystal structure influences S, metals have small thermo power while semiconductors can be doped with excess electrons or holes, increasing the magnitude of S (Chen, et *al.*, 2009). The sign of the thermo power determines which charged carriers dominate the electric transport (its negative when electrons dominate and positive when holes dominate). If the temperature difference between the two ends of a material is small, then the thermo power of a material is defined approximately as (Mc Gee, 1988):

$$S = \frac{\Delta V}{\Delta T} \quad \ldots\ldots (2.03)$$

and a thermoelectric voltage of ΔV is observed at the terminals. The absolute thermo power of the material of interest is rarely practically measured because electrodes attached to a voltmeter must be placed onto the material in order to measure the thermoelectric voltage inducing a thermoelectric voltage across one leg of the measurement electrodes. The measured thermo power then includes the thermo power of the material of interest and the material of the measurement electrodes and is written as (Ferreira and Kim, 2008):

$$S_{AB} = S_B - S_A = \frac{\Delta V_B}{\Delta T} - \frac{\Delta V_A}{\Delta T} \quad \ldots\ldots (2.04)$$

In addition, a measurement of the Thomson coefficient μ of a material yields the thermo power through the relation (Mc Gee, 1988):

$$S = \int \frac{\mu}{T} dT \quad \ldots\ldots (2.05)$$

The Seebeck effect is caused by charge carrier diffusion and phonon drag. Charge carrier in the materials will diffuse when one end of a conductor is at a different temperature from the other. Hot carriers diffuse from the hot end to the cold end of the conductor and vise versa (Chen, *et al.*, 2009). If the conductor were left to reach thermodynamic equilibrium, then this process would result in heat being distributed evenly throughout the conductor. The movement of heat (in the form of hot carriers) from one end to the other is a heat current and an electric current. As charge carriers are moving in a system where both ends are kept at a constant temperature difference, there is a constant diffusion of carriers. If the rate of diffusion of hot and cold carriers in opposite directions is equal, there is no net change in charge (Disalvo, 1999). The diffusing charges are scattered by impurities, imperfections and lattice vibrations or phonons. If the scattering is energy dependent, the hot and cold carriers will diffuse at different rates, creating a higher density of carriers at one of the materials and an electrostatic voltage. This electric field opposes the uneven scattering of carriers, and equilibrium is reached where the net number of carriers diffusing in one direction is canceled by charges that vary with temperature and electric field (Litnivov, 2011). Phonons are not always in local thermal equilibrium, they move against the thermal gradient. They lose momentum by interacting with electrons (or other carriers) and imperfection in the crystal. If the phonon-electron interaction is predominant, the phonons will tend to push the electrons to one end of the material, hence losing momentum and contributing to the thermoelectric field. This contribution is most important in the temperature region where phonon-electron scattering is predominant. This happens for;

$$T=\frac{1}{5}\vartheta_D \qquad (2.06)$$

where θ_D is the Debye temperature. At lower temperatures there are fewer phonons available for drag, and at higher temperatures they tend to lose momentum in phonon-phonon scattering instead of phonon-electron scattering (Walter, 2007).

2.5.2 Device Efficiency

The figure of merit Z for thermoelectric devices is defined as;

$$Z=\frac{S^2}{\rho K} \qquad (2.07)$$

Where ρ is the electrical resistivity, K is the thermal conductivity and S is the Seebeck coefficient. The dimensionless figure of merit ZT is formed by multiplying Z with the average temperature;

$$T=\frac{(T_2+T_1)}{2} \qquad (2.08)$$

ZT is a method for comparing the potential efficiency of devices using different materials. Greater ZT indicates a greater thermodynamic efficiency (Ferreira and Kim, 2008).

The efficiency of thermoelectric device for electricity generation is given by η, defined as (Mc Gee, 1988) ,

$$\eta=\frac{\text{energy provided to the load}}{\text{heat energy absorbed at the hot junction}} \qquad (2.09)$$

. The maximum efficiency η_{MAX} is defined as,

$$\eta_{MAX} = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+Z\overline{T}} - 1}{\sqrt{1+Z\overline{T}} + \frac{T_C}{T_H}} \quad \text{......(2.10)}$$

Where T_H is the temperature at the hot junction and T_C is the temperature at the surface being cooled. $Z\overline{T}$ is the modified dimensionless figure of merit, which takes into consideration the thermoelectric capacity of both thermoelectric materials being used in the device and is defined as:

$$Z\overline{T} = \frac{\left(S_\rho - S_n\right)^2 \overline{T}}{\left[\left(\rho_n k_n\right)^{\frac{1}{2}} + \left(\rho_\rho k_\rho\right)^{\frac{1}{2}}\right]^2} \quad \text{......(2.11)}$$

Where ρ is the electrical resistivity, T is the average temperature between the hot and the cold surfaces and the subscripts n and p denote properties related to the n and p type semiconducting thermoelectric devices. The efficiency of the thermoelectric device is limited by the Carnot efficiency, hence the T_H and T_C terms in η_{MAX} (Ferreira and Kim, 2008).

2.6 Generating Electricity from Heat Using Thermal Diodes

Heat gives electrons enough kinetic energy to boil off and jump a tiny gap creating a minuscule electric current. But the temperature needed to generate this current is very high, around 1000A °C. A thermal diode had been created which operates at 200A°C, still too high of a temperature to be used for computers. Instead of just trying to make the gap between the diode's electrodes smaller so that the electrons could easily traverse it, semiconductors in which adjacent electrodes are oppositely doped was used to form a PN junction. Essentially, one side has impurities added to it to make it electron rich while the other side has impurities added to make it electron defficient. An extremely electron-rich layer between the electrodes is created to yield more electricity. The availability of thermal diodes would greatly help increase the battery lives of portable device, not to mention help decrease the power requirements of many more electronic devices (Yang, 2002).

2.7 Generating Electricity from the Waste Heat in a Desktop Computer Using a Thermocouple

A Thermocouple is a junction between two different metals/alloys that produces a voltage related to a temperature difference. Every metal/alloy has a unique electronic and crystalline structure hence the allowed energy states and their electronic population will also be unique. When the two metals come in contact, the electrons in the metal with high energy will flow into the one with the lower energy until the excess electrons in the metal of lower energy builds up a reverse EMF (electromotive force) which opposes the flow; this occurs when all the electrons in both energies come to common Fermi energy E_f intermediate between the two (McGee, 1988). Thermocouples are a widely used type of temperature sensor for measurement and control and can also be used to convert heat into electric power. Thermocouple operation is based on the Seebeck effect or thermoelectric effect in which any conductor subjected to a thermal gradient generates a voltage (Long, 2001). Any attempt to measure this voltage necessarily involves connecting another conductor to the “hot” end. This additional conductor will then also experience the temperature gradient and develop a voltage of its own which will oppose the original. Using a dissimilar metal to complete the circuit creates a circuit in which the two legs generate different voltages, leaving a small difference in voltage available for measurement. This difference increases with temperature and is between 1 and 70 microvolt per degree Celsius ($\frac{\mu V}{^{\circ}C}$) for standard metal combinations (Ramsden, 2000). The voltage is not generated at the junction of the two metals of the thermocouples but rather along that portion of the length of the two dissimilar metals that is subjected to a temperature gradient. Because both lengths of dissimilar metals experience the same temperature gradient, the end result is a measurement at the thermocouple junction. The electrical energy generated by a thermocouple is converted from the heat which must be supplied to the hot side to maintain the electric potential. A continuous flow of heat is necessary because the current flowing through the thermocouple tends to cause the hot side to cool down and the cool side to heat up (peltier effect; applying a voltage to a thermocouple creates a temperature differential between two sides) (Long, 2001).

2.8 Theoretical Analysis

The first law of thermodynamics requires that in steady operation the energy input into a system be equal to the energy output from the system. Considering that the only form of energy leaving the computer device is heat generated as the current flows through the resistive element; that is we assume a classic “electric oven” then the heat generation or the cooling load of the computer is equal to the power consumption. Therefore, the heat generation is given by;

$$Q = VI \quad \text{..} \quad (2.12)$$

Where V is the voltage applied and I is the electric current at the entrance of the computer (Çengel, 1998). The resistive elements in the computer start radiating heat soon after the computer is plugged in and we can feel the emitted radiation energy by holding our hands against the computer. A black body is a perfect emitter and a perfect absorber of radiation and emits radiation energy uniformly in all directions (Modest, 1993). If we assume that the material used in making the motherboard is a blackbody, then the radiation energy emitted per unit time and per unit surface area is given by;

$$E = \sigma T^4 \quad \text{..} \quad (2.13)$$

Where $\sigma = 5 \cdot 67 \times 10^{-8} \frac{W}{m^2} \cdot k^4$ is the Stefan –Boltzmann constant and T is the absolute temperature of the surface in K. Thermocouples can be connected in series to form a thermopile, where all the hot junctions are exposed to a higher temperature and all the cold junctions to a lower temperature, the output is the sum of the voltages across the individual junctions, giving larger voltage and power output (Long, 2001). For typical metals used in thermocouples, the output voltage increases almost linearly with the temperature difference. For precise measurements, non-linearity must be corrected. The nonlinear relationship between the temperature difference (ΔT) and the output voltage (µV) of a thermocouple can be approximated by a polynomial

$$\Delta T = \sum_{n=0}^{N} a_n v^n \quad \text{..} \quad (2.14)$$

(Ramsden, 2000). The coefficients of type K Thermocouple are given in table 2 (Buschow, 2001).

Table2.2. Polynomial coefficients 0-500ºC

N	Type k
1	25.08355
2	$7.860106\text{x}10^{-2}$
3	$-2.503131\text{x}10^{-1}$
4	8.315270^{-2}
5	$-1.228034\text{x}10^{-2}$
6	$9.804036\text{x}10^{-4}$
7	$-4.413030\text{x}10^{-5}$
8	$1.057734\text{x}10^{-6}$
9	$-1.052755\text{x}10^{-8}$

The Thermo power produced by the thermocouple is given by;

$$S = \frac{\Delta V}{\Delta T}$$

The figure of merit for the thermopile is given by:

$$Z = \frac{S^2}{K\rho}$$

And the dimensionless figure of merit ZT is formed by multiplying Z with the average temperature

$$T = \frac{T_2 + T_1}{2}$$

The maximum thermodynamic efficiency η max of the thermopile is given by:

$$\eta_{MAX} = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+Z\overline{T}} - 1}{\sqrt{1+Z\overline{T}} + \frac{T_H}{T_C}}$$

Cold junction compensation can be performed by computation using look up tables and polynomial interpolation (Baker, 2000).

CHAPTER THREE
MATERIALS AND METHODS

3.1 Materials

Dell desktop computer (P4:2.8GHZ, RAM: 5.2MB, HDD: 40GB), Compaq desktop computer (P3:976MHZ, RAM: 256MB, HDD: 20GB), Compaq desktop computer (P4:2.0 dual core processor, RAM: 2GB, HDD: 250GB), Compaq CRT monitor, digital multimeter, a metre rule, a resistance box, four type J (iron-constantan) thermocouples, 2286/2285 data logger were used for the study.

3.2 Method

3.2.1 Heat Generation Measurement

To get the heat generation, the current I from the PSU to the motherboard and HDD and the voltage V across the motherboard and HDD of the desktop computers under varying processor workloads was measured using a digital multimeter as shown in appendix A (plates A1 and A2). However, the current I from the PSU to the HDD and the voltage V across the HDD of the Compaq P4 computer could not be measured owing to its location in the CPU. A resistance of 10Ω was connected in series with the components when taking the current measurements. The processor workload was varied as shown in table 3.1 for all the desktop computers. These processes were chosen because they are frequently used in personal computers. The power rating of the Dell P4 and the Compaq P4 computers are; input voltage: ac 115V; 8A, dc 230V; 4A, frequency 60Hz, output 450watts. The optimum temperature for the operation of the processor of the Compaq P4 computer was 40°C 37°C.

Table 3.1: Type of process and the corresponding processor workload

Number of processes	Type of process and Process load	Processor workload
Idle		
One process	Window media player (14.4MB)	14.4MB
Two processes	Window media player (14.4MB) and scanning (Avast antivirus- 38.6MB)	53MB
Three processes	Window media player (14.4MB), scanning (Avast antivirus- 38.6MB) and VLC media player(18.5MB)	71.5MB
Four processes	Window media player (14.4MB), double scanning (Avast antivirus- 38.6MB) and VLC media player	110.1MB

3.2.2 Thermoelectric Voltage Measurement

Type J thermocouples were connected to the heat generation modules (processor, north bridge, south bridge and HDD) to tap the waste heat from the desktop computers and convert it to thermoelectric energy as shown in appendix B (plates B1and B2). The processor workload was varied as in section 3.2.1 above. The thermocouples were terminated at the isothermal input connector (option -175) of the data logger. 2286/5 data logger was used to measure the thermocouples temperature and the corresponding thermoelectric voltage generated at room temperature. The thermoelectric voltage measurements were done for the computers under varying processor workloads, first with the heat sinks on then with the heat sinks off. The processor heat sink and fan were removed for the Dell P4 computer; while for the Compaq P3 computer the processor fan was removed while the processor heat sink remained on as the processor could not work without the heat sink. However, the heat sink of the Compaq P4 computer processor could not be removed as the processor could not work without a heat sink while the processor fan could not be removed because of its location.

3.2.3 Determination of the Reliability of the Usage of the Generated Thermoelectric Voltage to Power the Desktop Computer.

To determine the reliability of the usage of the generated thermoelectric voltage to power the desktop computer, the amounts of thermoelectric voltage generated was compared with the power consumption of the desktop computers. The power consumption of the desktop computers and the thermoelectric voltage generated from the waste heat of the desktop computers under varying processor workload was measured as described in sections 3.2.1 and 3.2.2 above respectively.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Heat Generation in a Computer.

Heat Generation = Power consumption i.e. $Q = VI$

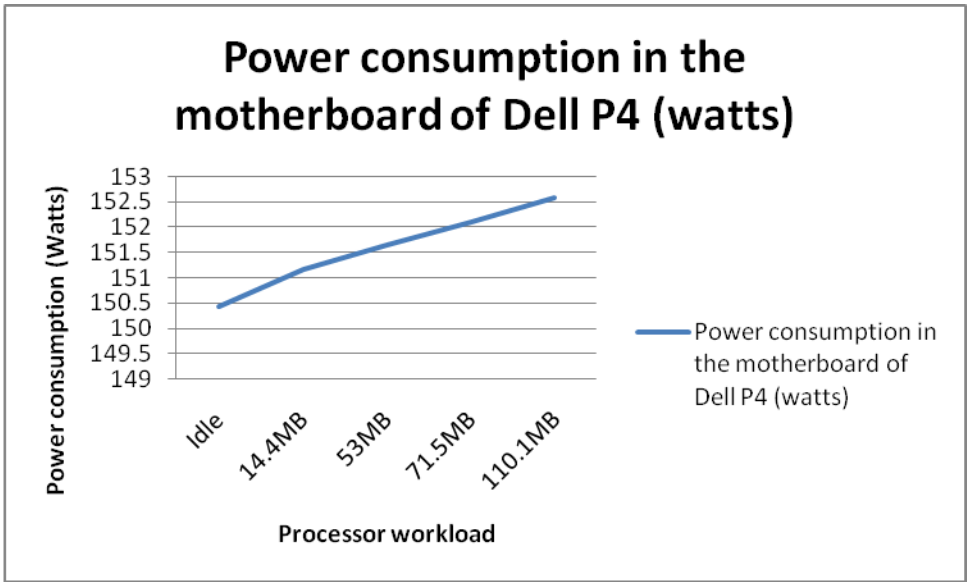

Fig 4.1: Increase in power consumption with the number of processes in the motherboard of Dell P4 computer.

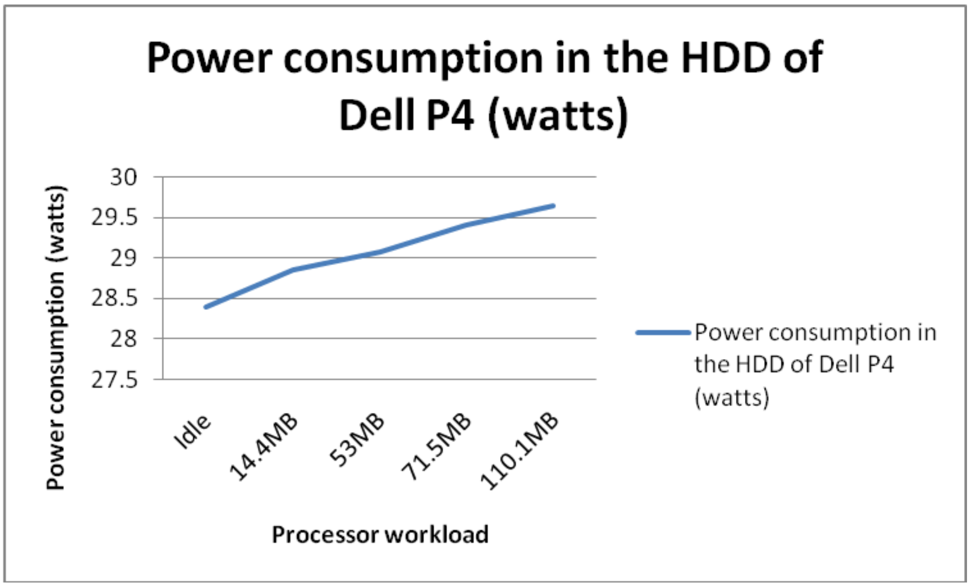

Fig 4.2: Increase in power consumption with the number of processes in the HDD of Dell P4 computer**.**

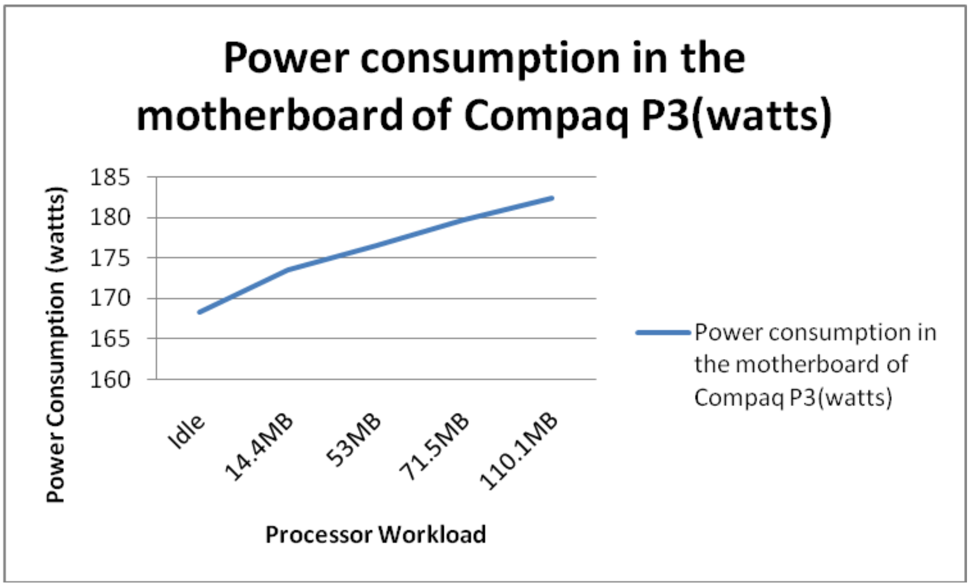

Fig 4.3: Increase in power consumption with the number of processes in the motherboard of Compaq P3 computer.

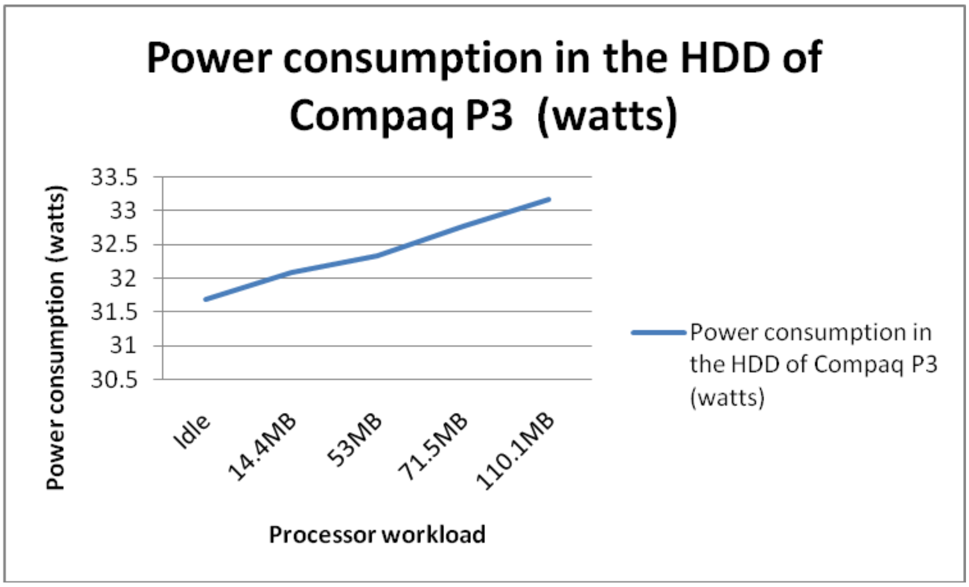

Fig 4.4: Increase in power consumption with the number of processes in the HDD of Compaq P3 computer.

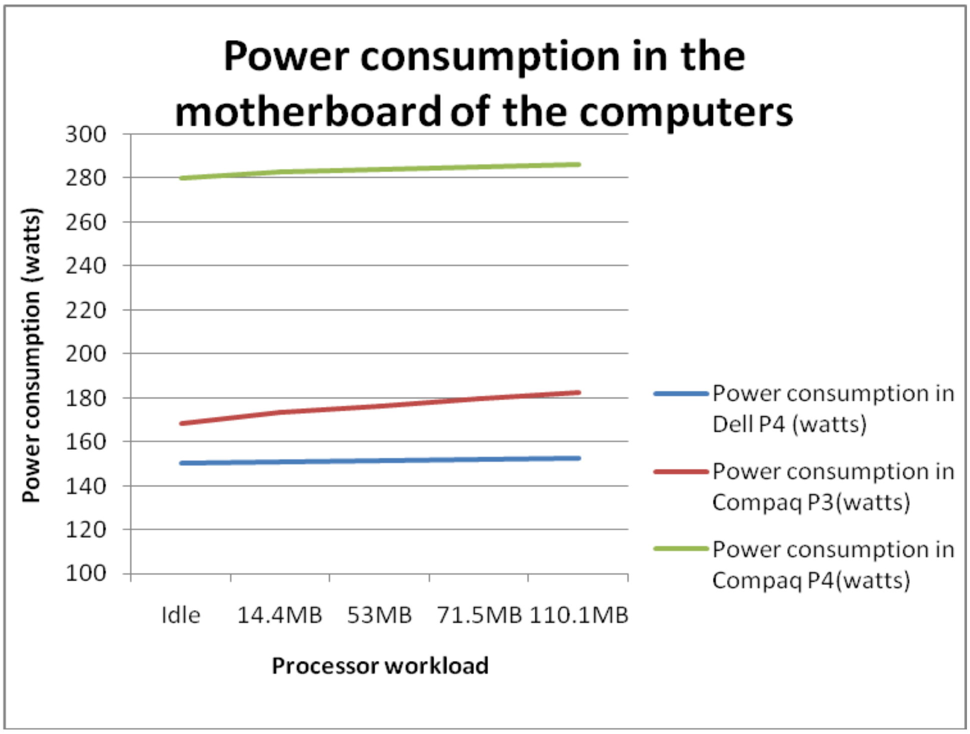

Fig 4.5: Comparison of power consumption in motherboard of the desktop computers

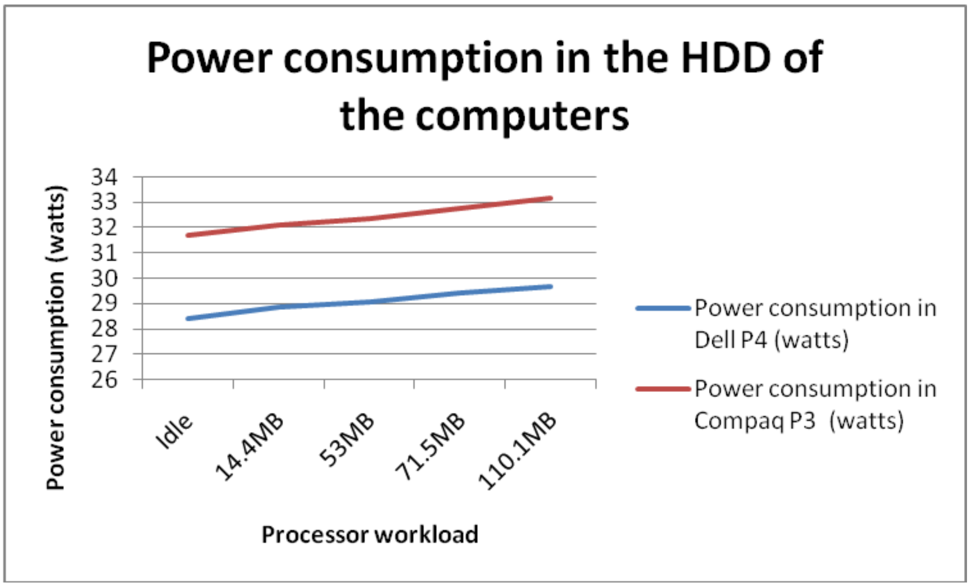

Fig 4.6: Comparison of power consumption in the HDD of the desktop computers

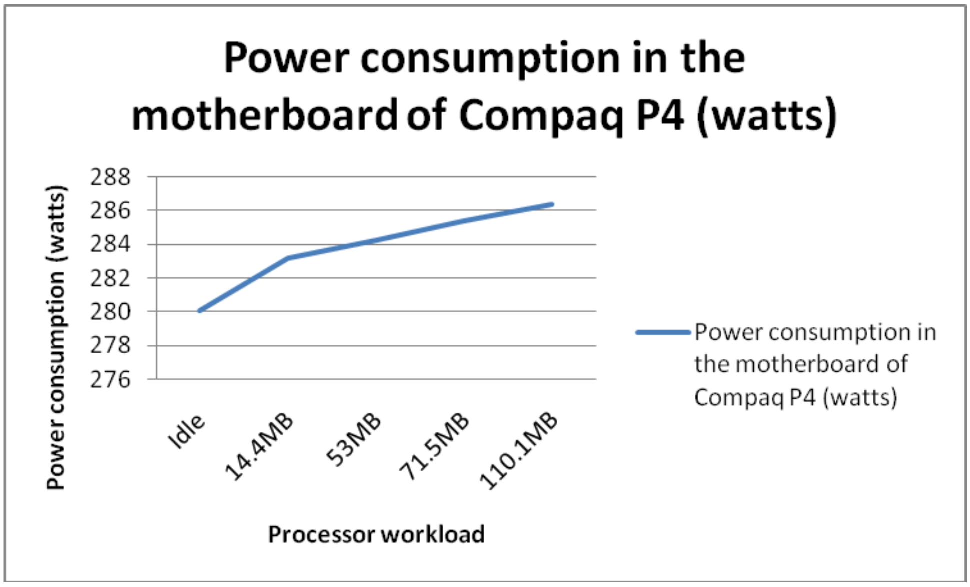

Fig 4.7: Increase in power consumption with the number of processes in the motherboard of Compaq P4 computer.

4.1.2 Thermoelectric Voltage Generated from Computer Waste Heat Using a Thermocouple

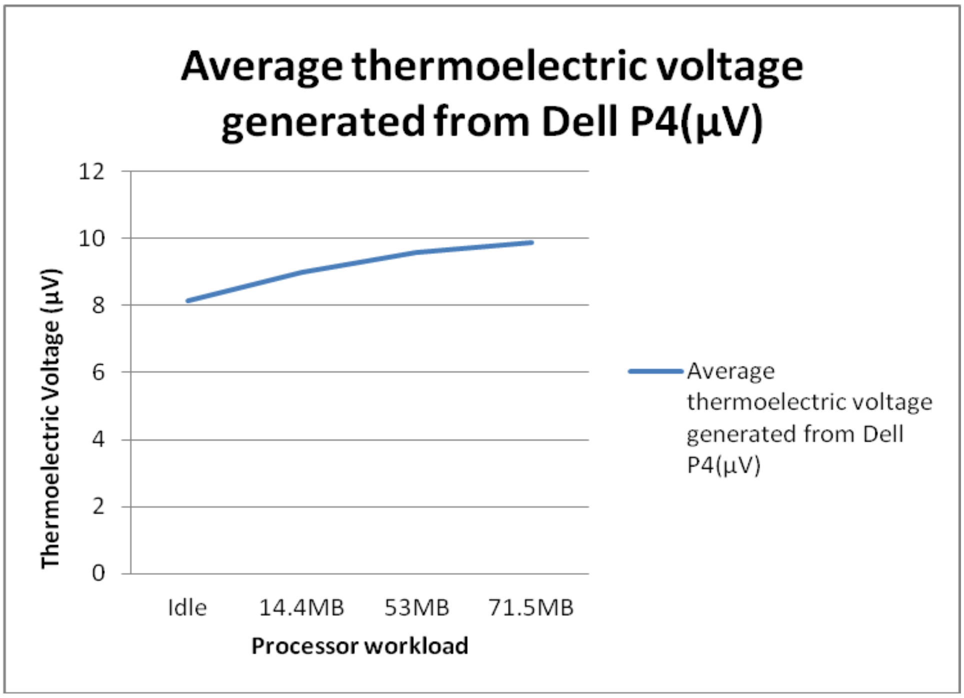

Fig 4.8: Thermoelectric voltage generated from waste heat in Dell P4 computer (with heat sinks ON) under varying processor workload.

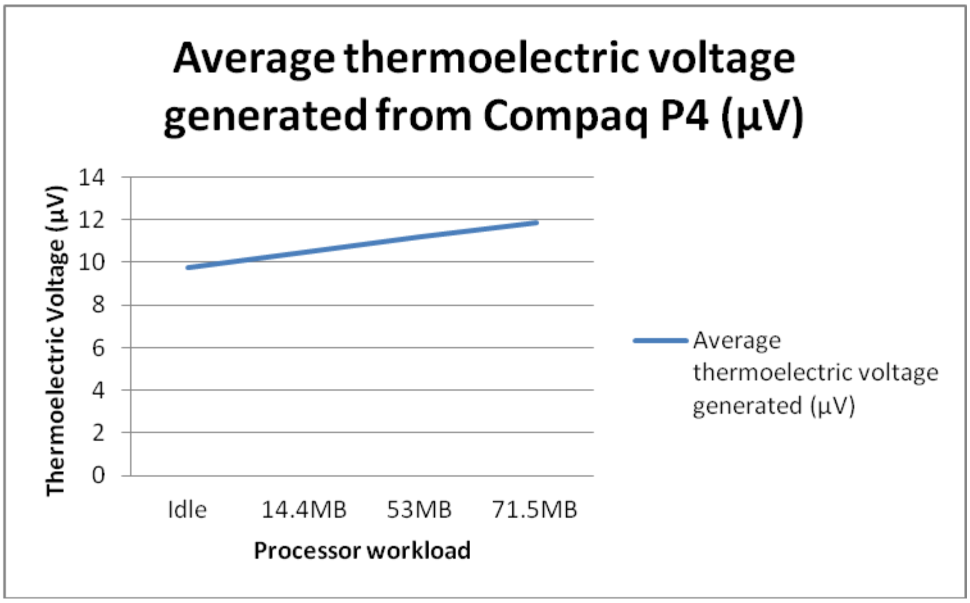

Fig 4.9: Thermoelectric voltage generated from waste heat in Compaq P4 computer (with heat sinks ON) under varying processor workload

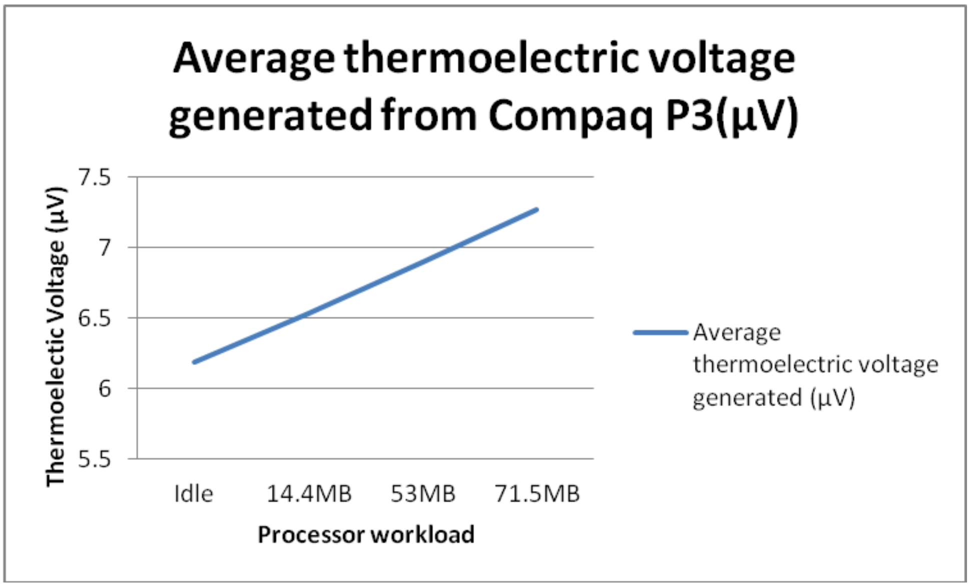

Fig 4.9.1: Thermoelectric voltage generated from waste heat in Compaq P3 computer (with heat sinks ON) under varying processor workload.

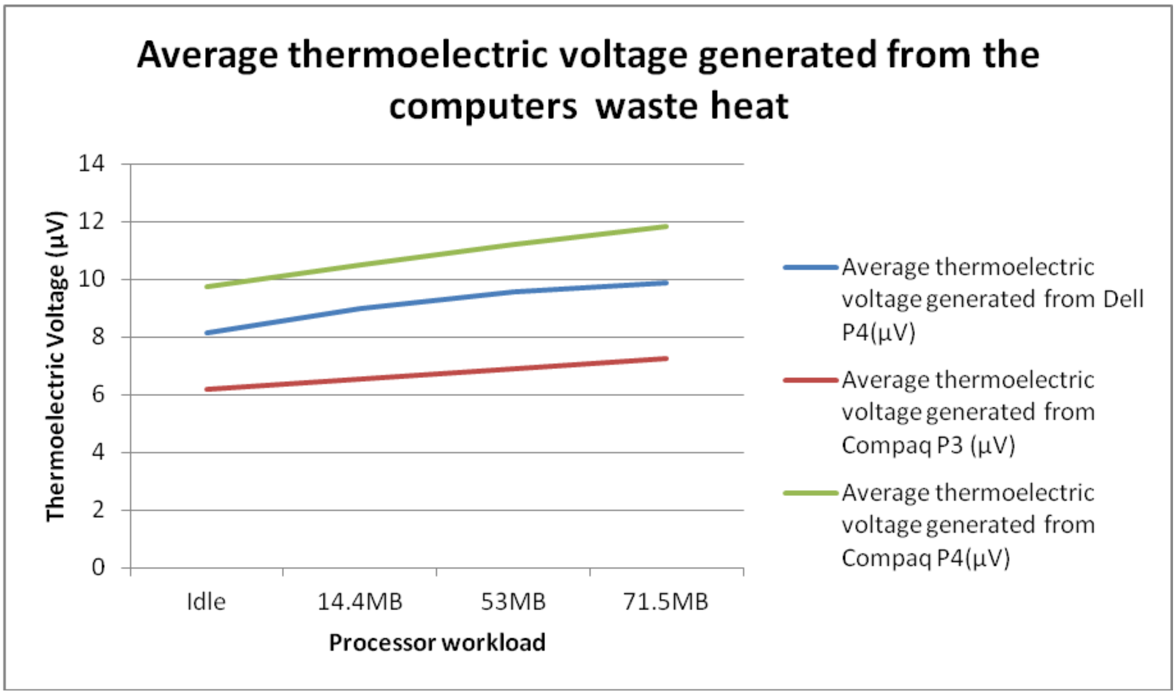

Fig 4.9.2: Comparison of thermoelectric voltage generated by the computers waste heat

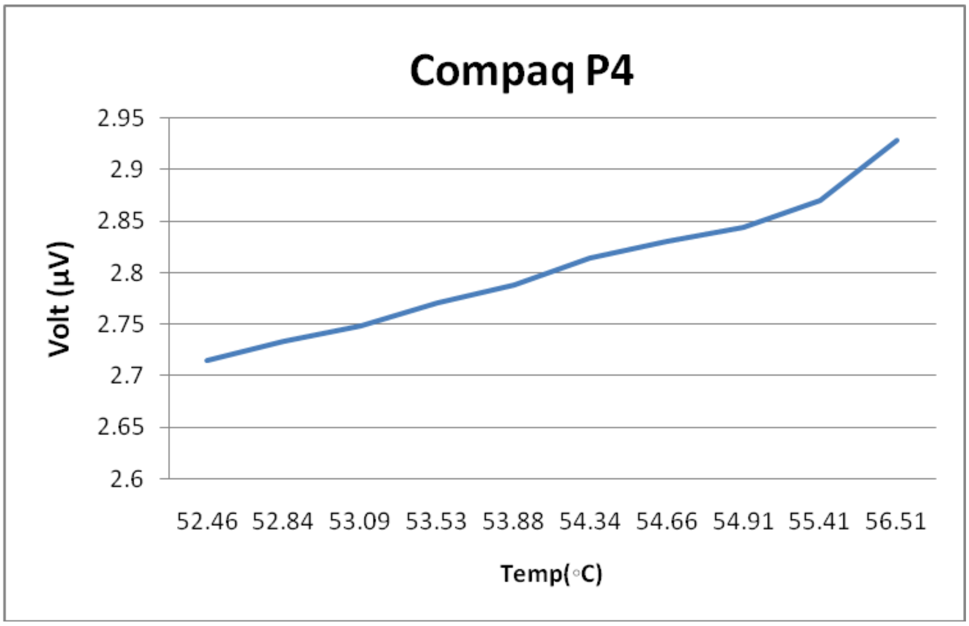

Fig 4.9.3: Increase in thermoelectric voltage with temperatures in the processor of Compaq P4 computer

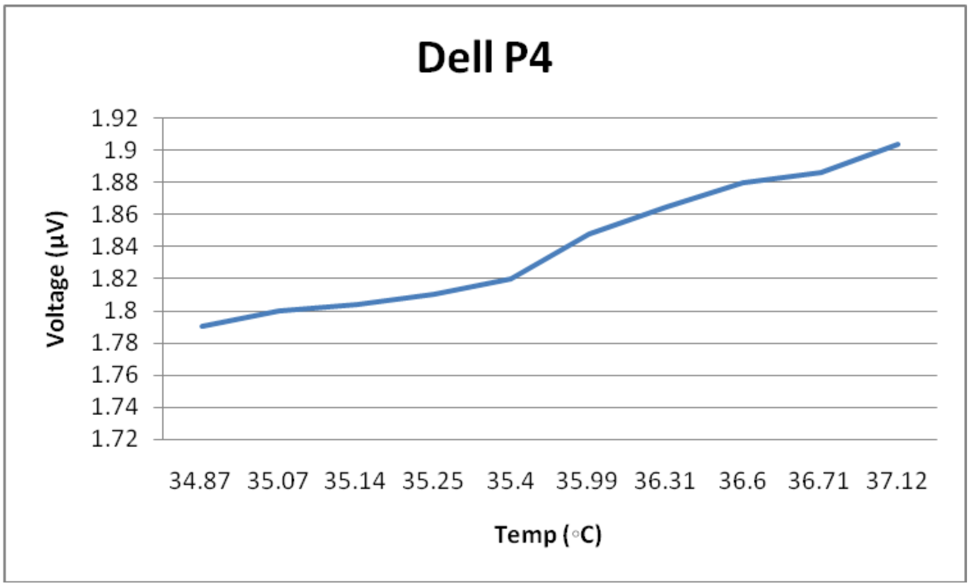

Fig 4.9.4: Increase in thermoelectric voltage with temperatures in the processor of Dell P4 computer.

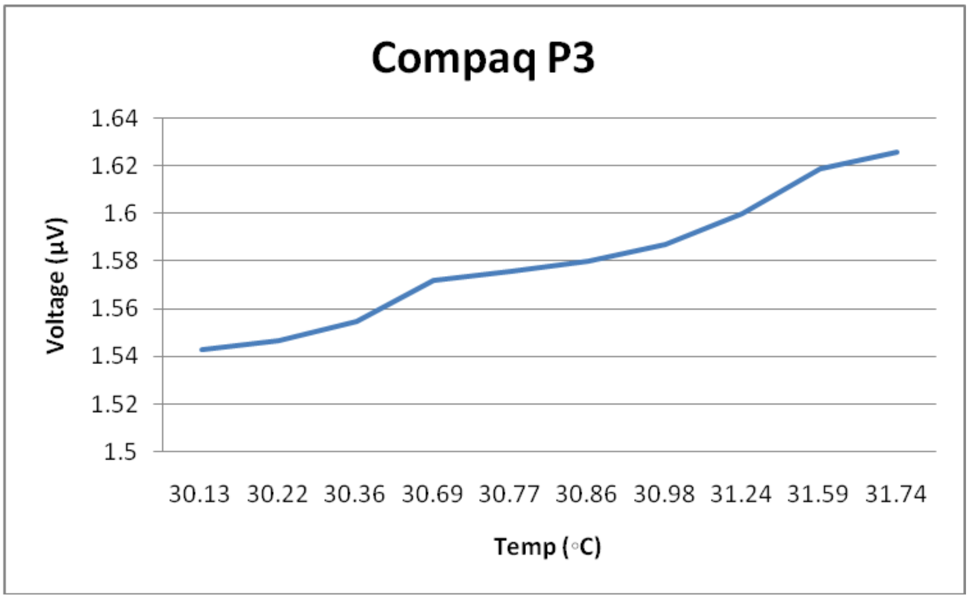

Fig 4.9.5: Increase in thermoelectric voltage with temperatures in the processor of Compaq P3 computer**.**

4.2 Discussion

4.2.1 Study of Heat Generation in Computers

Figures 4.1-4.7 shows that the power consumption of the computers increases with an increase in the number of processes the computers run. Because computer components depend on the flow of electric current to process information, an increase in the workload implies that more current will be drawn. The graphs in figures 4.1-4.7 shows an almost linear relation after an idle mode because in idle state the processor goes into a low power mode; video output is turned off and the hard disks spin down, then the power consumption thereafter is mainly dependent on the processor workload.

Results show that computers generate a lot of heat. Compaq P4, Dell P4 and Compaq P3 generated 286.33, 152.57 and 182.37 joules per second respectively. If for example the computers were in operation for an hour, the heat generated in the motherboard of Compaq P4, Dell P4 and Compaq P3 computers for the various workloads would be 1,008,180-1,030,788J, 541,548-549,252 J and 606,060-656,532 J respectively ($H = VIt$). The heat generated by the computers in an hour therefore is enough (for example) to raise the temperature of one kilogram of water by 100^0C ($H = mc\Delta\theta = 1\times 4200\times 100 = 420,000J$).

The power consumption of the Compaq P3 computer was found to be higher than that of the Dell P4 computer for the various workloads while the power consumption of the Compaq P4 computer was observed to be much higher than both of the Compaq P3 and Dell P4 computers for the various workloads as shown in figure 4.6. The gradient of graphs in figures 4.1, 4.3 and 4.7 are 0.522, 3.422 and 1.475 $\frac{watts}{MB}$ respectively and that of figures 4.2 and 4.4 are 0.308 and $0.364\frac{watts}{MB}$. The gradients show that Compaq P3 has the highest power consumption per megabyte of load followed by Compaq P4 and lastly Dell P4 computer; this is attributed to the make of the components and the number of components. The amount of power consumption found for the HDDs was as expected (karabuto, 2005). The heat generation was highest in the Compaq P4 computer followed by the Compaq P3 computer and lastly Dell P4 computer as shown in figures 4.5-4.6.

Computational power was observed to be highest in Compaq P4 computer followed by Dell P4 and lastly Compaq P3. The Compaq P4 computer which had the highest computational power of the three computers equally had the highest power consumption/heat generation. The higher heat generation in Compaq P3 compared to Dell P4 can only be attributed to its components make because a comparison of the components of the computers as shown in table 4.1 implies higher heat dissipation in Dell P4 computer. The higher heat generation in Compaq P4 computer compared to the Dell P4 computer is attributed to both the computational power and the components make of the computers while the higher heat dissipation in Compaq P4 computer compared to the Compaq P3 computer is attributed to the number of components and the computational power of the computers.

Table 4.1: Comparison of components of the computers.

Components	Compaq P3	Dell P4	Compaq P4
No of capacitors	19	47	42
No of major transistors	6	9	12
No of ICs	3	4	4
No of USB ports	3	8	6
No of expansion slots	1	5	4
No of display slots	4	5	2
No of HDD slots	2	4	4
Processor speed	1.4Hz	2.8GHz	2.0 dual core

4.2.2 Study of the Optimum Thermoelectric Voltage that can be Generated from Computer Waste Heat Using Thermocouples.

The thermocouples measurements were taken with room temperature as the reference junction. Thermocouples terminated at the isothermal input connector of the 2286/5 data logger use permanently stored voltage/temperature compensation and voltage/temperature linearization algorithms so cold junction compensation had been performed for the thermoelectric voltage measurements taken.

The thermal energy emitted per unit time in the desktop computers under the various processor workloads is calculated from $E = \sigma T^4 A$ Where $\sigma = 5 \cdot 67 \times 10^{-8} \frac{W}{m^2} \cdot k^4$ is the Stefan –Boltzmann constant and T is the absolute temperature of the surface in K and A the surface area of the body emitting thermal radiation (with the assumption that the emitting surfaces are blackbodies). Limited to the heat generation modules considered, thermal energy of 14.18-15.328 J/s, 11.51-13.093 J/s and 9.756-10.357 J/s was emitted by Compaq P4, Dell

P4 and Compaq P3 computers respectively after 100s of operation: these values form a fraction of the total heat generated by the computer components under consideration because heat transfer in computer components occur simultaneously by conduction, convection and radiation. The thermal energy emitted by the computer components increase with increase in temperature and processor workload as shown in table B10 (appendix B) since the generated heat increases with increase in processor workload.

The temperature and the thermoelectric voltage generated from the waste heat of the desktop computers increase with an increase in the processor workload as shown in tables B1-B6 (appendix B) and figures 4.8-4.9.1 respectively since the generated heat increases with increase in processor workload. The variation of the thermoelectric voltage generated with the temperatures was as expected (Mc Gee, 1988). Figures 4.8- 4.9.2 show that small amounts of thermoelectric voltage can be generated from computer waste heat using thermocouples. Limited to the heat generation modules considered, a thermoelectric voltage of 9.740-11.853μV, 8.134-9.889μV and 6.191-7.269μV was generated from the generated heat of Compaq P4, Dell P4 and Compaq P3 computers respectively, so more thermoelectric voltage is generated from the waste heat of Compaq P4 computer followed by Dell P4 and lastly Compaq P3 as shown in figure 4.9.2.

Figures 4.9.3-4.9.5 and table's B1,B3,B4,B6,B7 (appendix B) show that the thermoelectric voltage generated increases with increase in temperatures since thermocouples operation is based on Seebeck effect in which any conductor subjected to a thermal gradient generates a voltage. However, with the heat sinks off as described in section 3.2.2, a faster rise in temperature hence thermoelectric voltage generated was observed in the processor of the Dell P4 computer, the processor temperature reached a maximum at 83.13˚C (after which it blew off) as shown in appendix B (Table B3). Even though the processor of the Compaq P3 computer could not work without a heat sink, an increase in the processor temperature and thermoelectric voltage generated was observed compared to when the processor had both the fan and the heat sink as shown in appendix B (Table B6). The fact that Compaq P3 computer could not work without a heat sink implies that it generates more heat than the Dell P4 computer.

4.2.3 Study of the Reliability of Reusing the Waste Heat from a Computer to Generate Thermoelectric Voltage to Power the Computer.

The thermoelectric voltage generated from the waste heat of the desktop computers under varying processor workloads using thermocouples is in the order of microvolts which is little compared to the power consumption of the desktop computers as shown in tables' 4.2-4.4 (Heat Generation = Power consumption i.e. $Q = VI$)

Table 4.2: Comparison of heat generation and the average thermoelectric voltage generated from the heat in Dell P4 computer (with heat sinks ON) under varying processor workload

Processor workload	Heat generation in the motherboard (J/s)	Heat generation in the HDD (J/s)	Average thermoelectric voltage generated (μV)
Idle	150.43	28.39	8.134
14.4MB	151.16	28.85	8.978
53MB	151.63	29.07	9.575
71.5MB	152.10	29.41	9.889

Table 4.3: Comparison of heat generation and the average thermoelectric voltage generated from the heat in Compaq P3 computer (with heat sinks ON) under varying processor workload.

Processor workload	Heat generation in the motherboard (J/s)	Heat generation in the HDD (J/s)	Average thermoelectric voltage generated (μV)
Idle	168.35	31.68	6.191
14.4MB	173.47	32.08	6.531
53MB	176.57	32.32	6.891
71.5MB	179.65	32.76	7.269

Table 4.4: Comparison of heat generation and the average thermoelectric voltage generated from the heat in Compaq P4 computer (with heat sinks ON) under varying processor workload.

Processor workload	Heat generation in the motherboard (J/s)	Average thermoelectric voltage generated (μV)
Idle	280.05	9.740
14.4MB	283.13	10.498
53MB	284.20	11.221
71.5MB	285.32	11.853

The maximum thermo power generated by the type J thermocouples from the waste heat of the desktop computers is calculated as follows using equation 2.3;

Dell P4 desktop computer, $S = \frac{3.325}{63.95} = 0.05199\,\mu\text{V}/^{\circ}\text{C}$

Compaq P4 desktop computer, $S = \frac{4.454}{84.99} = 0.0524\ \mu\text{V}/^{\circ}\text{C}$

Compaq P3 desktop computer, $S = \frac{2.053}{39.91} = 0.0514\ \mu\text{V}/^{\circ}\text{C}$

Dell P4 processor with the heat sink and fan removed, $S = \frac{4.354}{83.13} = 0.0524\ \mu\text{V}/^{\circ}\text{C}$

Compaq P3 processor with the fan removed, $S = \frac{2.343}{45.41} = 0.05159\ \mu\text{V}/^{\circ}\text{C}$. The average maximum thermo power produced by the thermocouple is therefore 0.052 μV/°C. Type J thermocouples positive wire (iron) has electrical resistivity of 9.67μΩ-cm and a thermal conductivity of 0.162s-cm^2-°C while the negative wire (constantan) has electrical resistivity of 48.9μΩ-cm and a thermal conductivity of 0.0506s-cm^2-°C (Mc Gee, 1988). The figure of merit for the thermocouple positive wire is calculated as follows, using equation 2.8;

$$Z = \frac{0.052^2}{9.67 \times 0.162} = 0.00176$$

And that of the thermocouple negative wire is;

$$Z = \frac{0.052^2}{48.9 \times 0.0506} = 0.00109$$

The dimensionless figure of merit can be approximated to be;

$$Z\overline{T} = \frac{63.478 \times 0.001425}{2} = 0.045$$

The values obtained for the thermocouple dimensionless figure of merit indicates a low thermodynamic efficiency for the thermocouples. The maximum thermodynamic efficiency of the thermocouple can be approximated, using equation 2.92 as;

$$\eta_{\max} = \frac{84.99-19}{84.99}\frac{\sqrt{1+0.045}-1}{\sqrt{1+0.045}+\frac{19}{84.99}} = 0.0137 = 1.37\%$$

With 100% efficiency of the thermocouples the average thermoelectric voltage generated from the waste heat of the desktop computers under the varying processor workloads would be 0.711-0.865V, 0.594-0.722V and 0.452-0.531V for the Compaq P4, Dell p4 and Compaq P3 computers respectively, which are quite high compared to the values obtained. The maximum thermoelectric voltage that can be generated from the computers waste heat is highest in Compaq P4, followed by Dell P4 and lastly Compaq P3 as shown in figure 4.9.6. However, even if the thermocouples thermodynamic efficiency was 100%, the thermoelectric voltage generated from the waste heat of the desktop computers would not be enough to power the desktop computers.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- Compaq P4, Dell P4 and Compaq P3 generated heat at the rate of 286.33, 152.57 and 182.37 joules per second respectively.
- The thermoelectric voltage generated from the waste heat of the desktop computers using thermocouples is usable: 11.583 μV, 9.889 μV and 7.269 μV were generated from the waste heat of Compaq P4, Dell P4 and Compaq P3 desktop computers respectively.
- The thermoelectric energy generated from the waste heat of the desktop computers using thermocouples is not enough to power the desktop computers and hence cannot be a reliable source of electrical energy for the computer.

5.2 Recommendations

- The heat generated by computers should be tapped and converted to thermoelectric energy.
- The thermoelectric energy generated from computers waste heat can be used to subsidize the power requirements of the computer.

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APPENDICES

APPENDIX A

Heat dissipation in computers

Plate A1: Voltage and Current measuring circuit for the Dell desktop computers

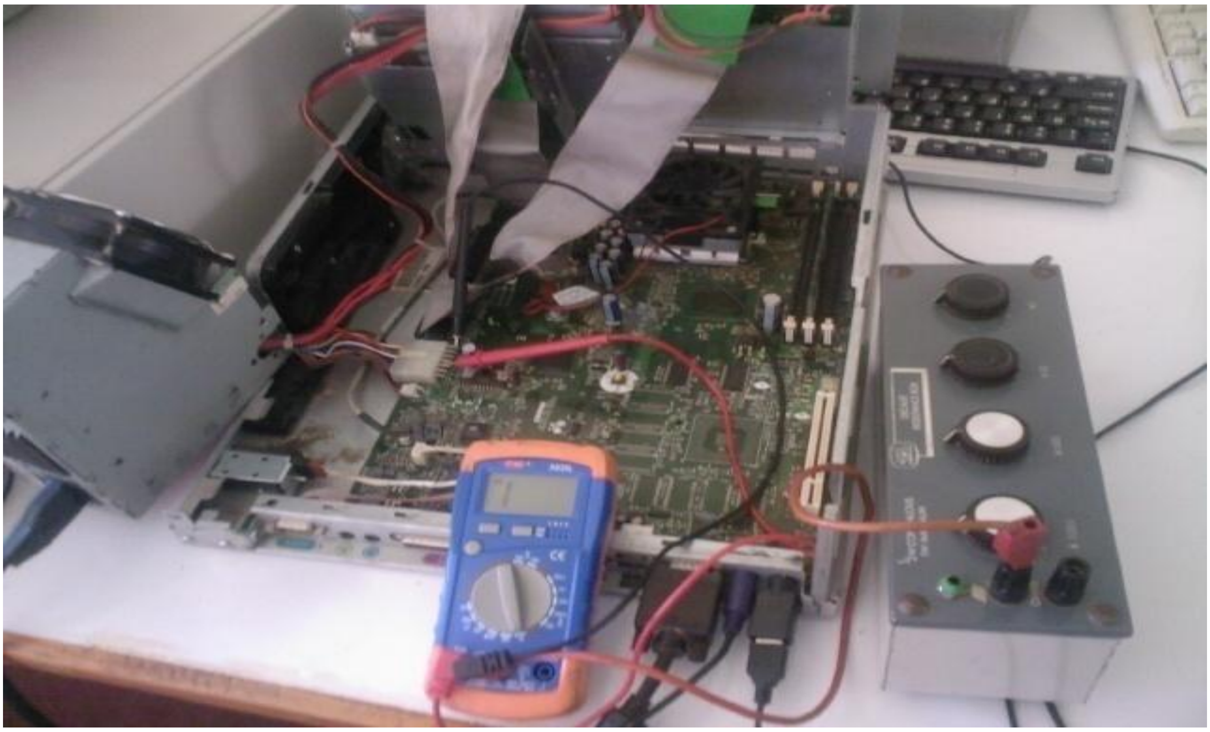

Plate A2: Voltage and Current measuring circuit for the Compaq desktop computers

The experimental error for the digital multimeter is 0.005V/A, that of the data logger is 0.0005µV and 0.05 for the metre rule.

Table A1: Power consumption (watts) in the Dell P4 desktop computer under varying processor workload

	Motherboard			HDD		
Processor workload	Voltage (V)	Current (A)	Power consumption (watts)	Voltage (V)	Current (A)	Power consumption (watts)
Idle	38.87	3.87	150.43	16.90	1.68	28.39
One Process	38.96	3.88	151.16	17.07	1.69	28.85
Two processes	38.98	3.89	151.63	17.10	1.70	29.07
Three processes	39.00	3.90	152.10	17.20	1.71	29.41
Four processes	39.02	3.91	152.57	17.24	1.72	29.65

Table A2: Power consumption (watts) in Compaq P3 desktop computer under varying processor workload

	Motherboard			HDD		
Processor workload	Voltage (V)	Current (A)	Power consumption (watts)	Voltage (V)	Current (A)	Power consumption (watts)
Idle	41.06	4.10	168.35	17.90	1.77	31.68
One Process	41.70	4.16	173.47	18.02	1.78	32.08
Two processes	42.04	4.20	176.57	18.06	1.79	32.32
Three processes	42.37	4.24	179.65	18.10	1.81	32.76
Four processes	42.71	4.27	182.37	18.22	1.82	33.16

Table A3: Power consumption (watts) in Compaq P4 desktop computer under varying processor workloads.

	Motherboard		
Processor workload	Voltage (V)	Current (A)	Power consumption (watts)
Idle	52.94	5.29	280.05
One process	53.22	5.32	283.13
Two processes	53.32	5.33	284.20
Three processes	53.43	5.34	285.32
Four processes	53.52	5.35	286.33

APPENDIX B

Thermoelectric Voltage generated from Computer Waste Heat

Plate B1; Thermocouples connected to the heat generation modules in the Compaq desktop computer

Plate B2; Thermocouples connected to the heat generation modules in the Dell desktop computer

Table B1: Thermoelectric voltage generated from waste heat in a Dell P4 desktop computer (with sinks ON) under varying processor workload.

Processor workload	Time (sec)	North bridge		South bridge		Processor		HDD		Total thermoelectric voltage (µV)
		Temp (◦C)	Volt (µV)	Temp (◦C)	Volt (µV)	Temp (◦C)	Volt (µV)	Temp (◦C)	Volt (µV)	
Idle	10	55.02	2.85	33.03	1.694	34.87	1.79	30.14	1.54	7.874
	20	56.27	2.91	33.43	1.715	35.07	1.8	30.48	1.56	7.985
	30	56.83	2.94	33.57	1.722	35.14	1.804	30.54	1.564	8.03
	40	57.25	2.97	34.04	1.747	35.25	1.81	30.67	1.57	8.097
	50	57.53	2.98	34.34	1.762	35.40	1.82	30.99	1.587	8.149
	60	57.77	2.99	34.54	1.773	35.99	1.848	31.12	1.594	8.205
	70	57.84	3	34.71	1.782	36.31	1.865	31.25	1.601	8.248
	80	58.00	3.009	34.87	1.79	36.60	1.88	31.75	1.627	8.306
	90	58.27	3.023	35.03	1.798	36.71	1.886	31.94	1.637	8.344
	100	58.41	3.029	35.40	1.82	37.12	1.904	32.03	1.641	8.394
One process	10	58.68	3.045	35.36	1.816	43.11	2.221	32.29	1.655	8.737
	20	59.11	3.067	35.61	1.828	43.21	2.227	32.40	1.661	8.783
	30	60.17	3.124	35.98	1.848	43.58	2.246	32.67	1.674	8.892
	40	60.62	3.148	36.23	1.86	43.75	2.255	32.80	1.68	8.943
	50	60.80	3.157	36.44	1.872	43.98	2.267	33.08	1.697	8.993
	60	60.93	3.164	36.72	1.886	44.07	2.272	33.41	1.714	9.036
	70	61.10	3.173	36.99	1.9	44.23	2.28	33.83	1.736	9.089
	80	61.25	3.181	37.18	1.91	44.52	2.297	34.03	1.746	9.134
	90	61.32	3.184	37.64	1.935	44.64	2.302	34.10	1.75	9.171
	100	61.51	3.195	37.95	1.951	44.75	2.308	34.37	1.764	9.218

Two processes	10	61.74	3.207	38.05	1.956	44.87	2.314	38.33	1.97	9.447
	20	61.82	3.211	38.25	1.967	44.90	2.315	38.53	1.981	9.474
	30	61.99	3.22	38.42	1.975	45.06	2.324	38.76	1.993	9.512
	40	62.10	3.226	38.60	1.985	45.12	2.327	38.92	2.002	9.54
	50	62.21	3.232	38.71	1.991	45.21	2.332	39.02	2.007	9.562
	60	62.34	3.239	38.88	1.999	45.33	2.338	39.21	2.017	9.593
	70	62.38	3.241	38.97	2.004	45.42	2.343	39.39	2.026	9.614
	80	62.49	3.247	39.12	2.012	45.56	2.351	39.56	2.035	9.645
	90	62.55	3.251	39.27	2.02	45.68	2.357	39.69	2.042	9.67
	100	62.73	3.26	39.40	2.027	45.76	2.361	39.92	2.054	9.702
Three processes	10	62.88	3.268	39.51	2.032	45.92	2.369	40.09	2.063	9.732
	20	62.92	3.271	39.61	2.038	46.05	2.377	40.36	2.077	9.763
	30	63.08	3.279	39.77	2.046	46.22	2.385	40.65	2.092	9.802
	40	63.26	3.288	39.86	2.051	46.33	2.391	40.86	2.104	9.834
	50	63.35	3.293	39.96	2.056	46.57	2.4	41.04	2.113	9.862
	60	63.43	3.298	40.07	2.062	46.72	2.411	41.41	2.132	9.903
	70	63.55	3.304	40.18	2.067	46.84	2.418	41.51	2.138	9.927
	80	63.7	3.312	40.26	2.072	46.92	2.422	41.7	2.147	9.953
	90	63.88	3.322	40.34	2.076	47.32	2.443	41.85	2.155	9.996
	100	63.95	3.325	40.42	2.08	47.97	2.477	42.02	2.164	10.046

Table B2: Average thermoelectric voltage generated from waste heat in Dell P4 computer (with heat sinks ON) under varying processor workload (room temperature=26°C).

Processor workload	Average thermoelectric voltage generated (μV)
Idle	8.134
One process	8.978
Two processes	9.575
Three processes	9.889

Table B3: Thermoelectric voltage generated from waste heat in a Dell P4 desktop computer (with heat sinks OFF) under varying processor workload.

Processor workload	Time (sec)	Processor (with heat sink and fan removed)	
Idle		Temp (◦C)	Volt (µV)
	10	30.72	1.573
	20	42.69	2.2
	30	50.42	2.607
	40	54.57	2.827
	50	57.92	3.005
	60	61.11	3.174
	70	64.75	3.368
	80	69.77	3.636
	90	74.46	3.888
One process	10	32.4	1.661
	20	48.61	2.511
	30	59.09	3.067
	40	62.96	3.273
	50	73.02	3.81
	60	82.72	4.332
	70	83.13	4.354

Table B4: Thermoelectric voltage generated from waste heat in Compaq P3 desktop computer (with heat sinks ON) under varying processor workload (room temperature=23˚C).

Processor workload	Time (sec)	North bridge		South bridge		Processor		HDD		Total thermoelectric voltage (μV)
		Temp (◦C)	Volt (μV)	Temp (◦C)	Volt (μV)	Temp (◦C)	Volt (μV)	Temp (◦C)	Volt (μV)	
Idle	10	32.17	1.649	27.29	1.396	30.13	1.543	28.24	1.444	6.032
	20	32.26	1.654	27.48	1.405	30.22	1.547	28.39	1.452	6.058
	30	32.48	1.665	27.61	1.412	30.36	1.555	28.56	1.461	6.093
	40	32.62	1.673	27.72	1.418	30.69	1.572	28.69	1.468	6.131
	50	32.86	1.686	27.85	1.424	30.77	1.576	28.89	1.478	6.164
	60	33.04	1.695	27.98	1.431	30.86	1.58	29	1.484	6.19
	70	33.19	1.703	28.1	1.437	30.98	1.587	29.16	1.492	6.219
	80	33.46	1.717	28.25	1.445	31.24	1.6	29.26	1.497	6.259
	90	33.69	1.729	28.51	1.458	31.59	1.619	29.48	1.509	6.315
	100	33.87	1.738	28.69	1.468	31.74	1.626	29.61	1.517	6.349
One process	10	34.04	1.747	28.82	1.475	31.82	1.631	29.76	1.523	6.376
	20	34.17	1.754	28.95	1.481	31.96	1.638	29.86	1.529	6.402
	30	34.31	1.761	29.07	1.487	32.13	1.647	29.96	1.534	6.429
	40	34.49	1.77	29.12	1.49	32.43	1.662	30.05	1.539	6.461
	50	34.69	1.781	29.21	1.495	32.65	1.674	30.15	1.544	6.494
	60	34.92	1.793	29.42	1.506	32.88	1.687	30.23	1.547	6.533
	70	35.27	1.811	29.56	1.513	33.06	1.696	30.38	1.556	6.576
	80	35.65	1.831	29.72	1.521	33.15	1.701	30.59	1.567	6.62
	90	35.71	1.834	29.84	1.528	33.44	1.716	30.7	1.572	6.65
	100	35.91	1.844	30	1.535	33.69	1.729	30.81	1.578	6.686
Two processes	10	36.08	1.853	30.15	1.544	33.82	1.736	30.99	1.587	6.72
	20	36.3	1.864	30.36	1.555	33.98	1.744	31.09	1.593	6.756
	30	36.41	1.87	30.48	1.561	34.22	1.756	31.2	1.598	6.785
	40	36.65	1.883	30.63	1.569	34.37	1.764	31.39	1.608	6.824
	50	36.8	1.89	30.78	1.576	34.62	1.777	31.52	1.615	6.858

	60	36.95	1.898	30.94	1.585	34.82	1.787	31.62	1.62	6.89
	70	37.15	1.908	31.27	1.602	35	1.797	31.7	1.624	6.931
	80	37.49	1.927	31.52	1.615	35.25	1.81	31.89	1.634	6.986
	90	37.74	1.94	31.77	1.628	35.49	1.822	31.95	1.637	7.027
	100	37.92	1.949	31.99	1.639	35.64	1.83	32.06	1.643	7.061
Three processes	10	38.09	1.958	32.06	1.643	35.83	1.84	32.30	1.656	7.097
	20	38.20	1.964	32.3	1.656	36.14	1.856	32.43	1.663	7.139
	30	38.40	1.975	32.47	1.665	36.36	1.868	32.58	1.671	7.179
	40	38.64	1.987	32.68	1.676	36.48	1.874	32.71	1.677	7.214
	50	38.88	1.999	32.81	1.683	36.78	1.889	32.86	1.686	7.257
	60	39.02	2.007	32.98	1.692	36.89	1.895	32.99	1.692	7.286
	70	39.18	2.015	33.15	1.701	37.06	1.904	33.17	1.702	7.322
	80	39.37	2.025	33.44	1.716	37.12	1.907	33.39	1.713	7.361
	90	39.61	2.038	33.59	1.723	37.28	1.916	33.51	1.719	7.396
	100	39.91	2.053	33.78	1.733	37.45	1.925	33.69	1.729	7.44

Table B5: Average thermoelectric voltage generated from waste heat in Compaq P3 computer (with heat sinks ON) under varying processor workload (room temperature=23°C).

Processor workload	Average thermoelectric voltage generated (µV)
Idle	6.191
One process	6.531
Two processes	6.891
Three processes	7.269

Table B6: Thermoelectric voltage generated from waste heat in Compaq P3 desktop computer (with heat sinks OFF) under varying processor workload (room temperature=24˚C)

Processor workload	Time (sec)	Processor (with heat sink ON but fan removed)	
Idle		Temp (◦C)	Volt (µV)
	10	42.95	2.213
	20	43.21	2.227
	30	43.58	2.246
	40	43.95	2.265
	50	44.1	2.273
	60	44.29	2.283
	70	44.55	2.297
	80	44.87	2.314
	90	45.02	2.322
	100	45.41	2.343

Table B7: Thermoelectric voltage generated from waste heat in Compaq P4 desktop computer (with heat sinks ON) under varying processor workload (room temperature=19˚C).

Processor workload	Time (sec)	North bridge		South bridge		Processor		HDD		Total thermoelectric voltage (µV)
Idle		Temp (◦C)	Volt (µV)	Temp (◦C)	Volt (µV)	Temp (◦C)	Volt (µV)	Temp (◦C)	Volt (µV)	
	10	62.45	3.245	35.32	1.814	52.46	2.715	32.22	1.652	9.426
	20	63.32	3.292	35.46	1.821	52.84	2.734	32.44	1.663	9.51
	30	63.97	3.326	35.79	1.838	53.09	2.748	32.69	1.676	9.588
	40	64.62	3.361	35.97	1.847	53.53	2.771	32.78	1.681	9.66
	50	64.98	3.379	36.12	1.855	53.88	2.789	32.91	1.688	9.711
	60	65.18	3.39	36.41	1.87	54.34	2.814	33.05	1.696	9.77
	70	65.85	3.426	36.62	1.881	54.66	2.831	33.25	1.706	9.844
	80	66.25	3.448	36.78	1.889	54.91	2.844	33.56	1.722	9.903
	90	66.6	3.467	36.98	1.9	55.41	2.871	33.78	1.733	9.971

	100	66.81	3.477	37.08	1.905	56.51	2.929	33.93	1.741	10.052
One process	10	67.19	3.498	37.17	1.91	57.32	2.973	34	1.745	10.126
	20	68.69	3.578	37.39	1.922	57.66	2.991	34.21	1.756	10.247
	30	69.64	3.629	37.54	1.929	57.85	3.001	34.32	1.762	10.321
	40	70.4	3.67	37.69	1.938	58.03	3.012	34.53	1.772	10.392
	50	71.55	3.732	37.8	1.943	58.27	3.023	34.61	1.777	10.475
	60	72.4	3.777	37.95	1.951	58.52	3.036	34.72	1.782	10.546
	70	73.25	3.822	38.12	1.96	58.74	3.048	34.8	1.787	10.617
	80	73.87	3.856	38.44	1.977	58.93	3.058	34.89	1.791	10.682
	90	74.19	3.872	38.51	1.98	59.21	3.073	34.98	1.796	10.721
	100	74.4	3.885	38.78	1.994	59.56	3.092	35.1	1.8	10.771
Two processes	10	75.25	3.93	39.12	2.012	60.14	3.122	35.17	1.806	10.87
	20	76.67	4.006	39.49	2.031	60.6	3.147	35.36	1.816	11
	30	77.69	4.061	39.69	2.042	60.84	3.159	35.45	1.82	11.082
	40	78.51	4.1	39.81	2.048	61.15	3.176	35.55	1.825	11.149
	50	79.55	4.162	40.15	2.066	61.59	3.199	35.61	1.829	11.256
	60	80.4	4.207	40.43	2.081	61.89	3.215	35.72	1.834	11.337
	70	80.87	4.232	40.79	2.099	62.12	3.227	35.83	1.84	11.398
	80	81.12	4.245	41.02	2.112	62.58	3.252	35.92	1.845	11.454
	90	81.55	4.269	41.44	2.134	62.77	3.262	36.03	1.85	11.515
	100	81.98	4.292	41.83	2.154	62.91	3.27	36.14	1.856	11.572
Three processes	10	82.12	4.299	42.15	2.171	63.12	3.281	36.25	1.862	11.613
	20	82.52	4.321	42.41	2.185	63.48	3.3	36.36	1.868	11.674
	30	82.71	4.331	42.69	2.199	63.74	3.314	36.43	1.871	11.715
	40	83.12	4.353	42.94	2.214	63.92	3.324	36.56	1.878	11.769
	50	83.52	4.375	43.12	2.222	64.25	3.341	36.62	1.881	11.819
	60	83.87	4.394	43.68	2.251	64.49	3.354	36.73	1.887	11.886
	70	84.06	4.404	44.01	2.268	64.76	3.368	36.84	1.892	11.932
	80	84.3	4.417	44.56	2.298	64.99	3.38	36.91	1.896	11.991
	90	84.69	4.438	44.91	2.316	65.2	3.392	36.98	1.9	12.046
	100	84.99	4.454	45.21	2.332	65.39	3.402	37.07	1.905	12.093

Table B8: Thermoelectric voltage generated from waste heat in Compaq P4 computer (with heat sinks ON) under varying processor workload (room temperature=19˚C).

Processor workload	Average thermoelectric voltage generated (µV)
Idle	9.740
One process	10.498
Two processes	11.221
Three processes	11.853

Table B9: Thermal energy emitted by the computers (after 100 s, with heat sinks ON) under varying processor workload

Processor workload	North bridge		South bridge		Processor		HDD		Total thermal energy emitted(J/s)
	Temp (K)	Thermal energy emitted (J/s)	Temp (K)	Thermal energy emitted (J/s)	Temp (K)	Thermal energy emitted (J/s)	Temp (K)	Thermal energy emitted (J/s)	
Dell P4									
Idle	331.41	0.838	308.40	0.462	310.12	3.068	305.29	7.142	11.510
14.4MB	334.51	0.870	310.95	0.477	317.75	3.381	307.37	7.338	12.066
53MB	335.73	0.882	312.40	0.486	318.76	3.425	313.09	7.900	12.693
71.5MB	336.95	0.895	313.42	0.492	322.97	3.609	315.02	8.097	13.093
Compaq P3									
Idle	306.87	0.366	301.69	0.152	304.74	2.347	302.61	6.890	9.756
14.4MB	308.91	0.376	303.00	0.155	306.69	2.408	303.81	7.000	9.939
53MB	310.92	0.386	304.99	0.159	308.64	2.47	305.06	7.120	10.135
71.5MB	312.91	0.396	306.78	0.163	310.45	2.528	306.69	7.27	10.357
Compaq P4									
Idle	339.81	0.68	310.07	0.254	329.51	5.849	306.93	7.397	14.180
14.4MB	357.4	0.743	311.78	0.259	332.56	6.068	308.1	7.511	14.581
53MB	354.98	0.81	314.83	0.270	335.91	6.316	309.14	7.638	15.034
71.5MB	357.99	0.838	318.21	0.281	338.39	6.505	310.07	7.704	15.328

Table B10: Surface area of the components of the computers

Computer (with heat sink ON)	Component	Dimensions	Surface area (m^2)
Compaq P4	Processor	$12.5cm \times 7cm$	8.75×10^{-3}
	North bridge	$3cm \times 3cm$	9×10^{-4}
	South bridge	$2.2cm \times 2.2cm$	4.84×10^{-4}
	HDD	$14cm \times 10.5cm$	1.47×10^{-2}
Dell P4	Processor	$9cm \times 6.5cm$	5.85×10^{-3}
	North bridge	$3.5cm \times 3.5cm$	1.225×10^{-3}
	South bridge	$3cm \times 3cm$	9×10^{-4}
	HDD	$14.5cm \times 10cm$	1.45×10^{-2}
Compaq P3	Processor	$8cm \times 6cm$	4.8×10^{-3}
	North bridge	$2.7cm \times 2.7cm$	7.29×10^{-4}
	South bridge	$1.8cm \times 1.8cm$	3.24×10^{-4}
	HDD	$14.5cm \times 10cm$	1.45×10^{-2}