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Bio-Thermoelectric Energy Harvesting in Space: Using Body Heat to Support Extra Vehicular Activity

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by

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Statement

This thesis was submitted for examination in September 2025. It does not necessarily represent the final form of the thesis as deposited in the University after examination.

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5. I have acknowledged all main sources of help;
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Abstract

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In this work, a novel approach to powering extravehicular activity in space using bio-thermoelectric energy harvesting has been investigated. An original experimental design, coupled with finite element analysis, execute an assessment of thermal and electric characterisation of a micro thermoelectric generator, within a representative thermal environment. Results yield discrete thermal and electrical behaviour with a maximum power output of $3.27\mu W$ at $\Delta T = 107$°C. With an average TEG gradient of 60°C throughout a 90 minute orbit, this study suggests that temperatures in LEO offer a basis for effective use of micro thermoelectric generators. Currently, inherently low power outputs limit prospects for this technology in EVA applications. Further experimental research is recommended in order to gain insight into the further effects from orbital environments on micro thermoelectric devices.

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Definitions and Abbreviations

ΔT	Temperature Difference/Gradient
EVA	Extra Vehicular Activity
EMU	Extravehicular Mobility Unit (Interchangeable with EVA suit and spacesuit)
TEG	Thermoelectric Generator
TE	Thermoelectric
f-TEG	Flexible Thermoelectric Generator
LEO	Low Earth Orbit
PSIA	Pounds Per Square Inch Absolute
ATM	Atmosphere
NASA	National Aeronautics and Space Administration
BOL	Beginning Of Life
EOL	End Of Life
Ahr	Ampere-Hour
PLSS	Portable Life Support System
EM	Electromagnetic
FEA	Finite Element Analysis
Al	Aluminium
Ag	Silver

Chapter 1

Introduction

The global space industry is undergoing a time of accelerating growth. Between 2019 and 2024, the number of objects launched into space per year surged by 386%. Attributable to declining launch costs, in conjunction with advancements in propulsion technology and miniature satellite design, the space domain has become fertile ground for rapid technological and infrastructural development. With the global space economy reaching revenues of $570B in 2023 [1] - forecasts predict the industry will total a valuation of $1-2 trillion by 2040 [12], [13]. As 2030 approaches, the International Space Station is scheduled for decommissioning and a plethora of national, multi-national and commercial space stations will spring up in it's place. Among those planned for construction are the Axiom Station, Orbital Reef, IRSO Space Station, Airbus LOOP, Lunar Gateway, as well as, the already completed, Tiangong Space Station [14]. What's more, in 2024, a record was set with 19 individuals simultaneously orbiting Earth - the highest number in history [15]. This trend is expected to continue due to significant investments by both government agencies and private companies, aiming to expand human presence in space. With this expansion comes an increased need for effective Extravehicular Activities (EVAs) to maintain and develop, the fast-growing, off-Earth infrastructure.

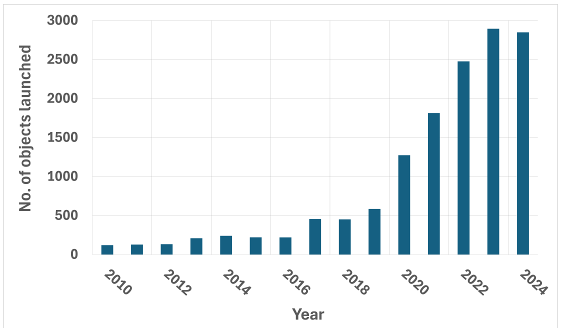

FIGURE 1.1: Bar chart showing objects launched into space worldwide from 2010 - 2024 [1].

EVA suits have enabled humankind to boldly go where no man has gone before; from setting foot upon the Moon, to performing spacewalks in orbit around Earth and beyond. These unique examples of cutting-edge technology provide protection to the relatively fragile human body of the occupant, against the extreme conditions of space, whilst generating an environment satisfying their physiological needs. Among these needs are temperature, pressure regulation and oxygen - without which, a human cannot function. Specific key biological requirements dictate that an individual's core temperature must be maintained at 37°C [16], therefore necessitating a suitable system capable of cooling and heating. Commonly, thermal regulation is achieved by pumping cool water through an integrated tubing system throughout the garment that can withstand continuous and peak metabolic rates outputted by the body under exertion [17]. As for pressure, low barometric pressure can cause nausea and headaches, better known as altitude sickness on Earth. The lowest limit corresponds to the Armstrong Limit ($\sim$1 psia), at which water will boil at room temperature, causing fatality in humans [18]. Unfortunately, matching the internal pressure of an EVA Suit to the atmospheric pressure of Earth at sea level is not viable as a sealed suit inflated to 1 atm (14.7 psia) would be rigid and restrict movement, upon introducing the suit to a vacuum. To solve this challenge, NASA EVA suits are pressurised to 4.3 psia with pure oxygen, allowing for good mobility whilst supporting the respiratory system of the occupant and ensuring sufficient oxygen supply at low pressures [19], [20]. Protective outer layers are designed to further shield against harmful radiation and potential space debris [21]. Spacesuits are incredibly sophisticated systems that deliver critical life support, under extreme conditions, whilst preserving the wearer's ability to move, communicate and conduct effective operations.

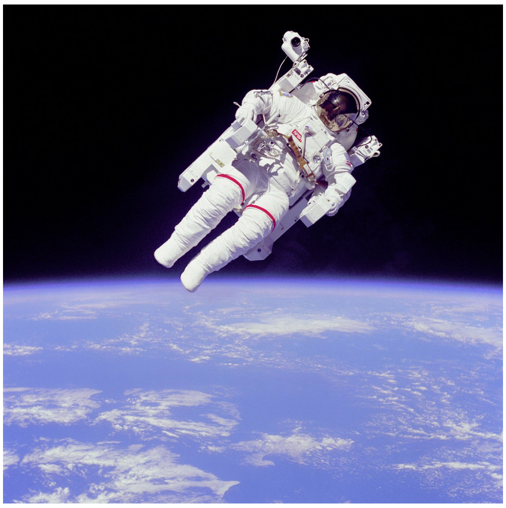

FIGURE 1.2: Untethered spacewalk taken by Astronaut McCandless (1984) [2].

Currently, the various systems running continuously to keep the user alive, comfortable and operationally effective are powered by battery packs. Historically, portable battery packs have provided a degree of autonomy to the astronauts after earlier missions such as Gemini, relied upon umbilical power. From at least 2010 onward, NASA replaced Silver/Zinc based battery systems for the Long Life Battery (LLB) composed of eighty (2.4 Ahr) lithium ion electrochemical cells, weighing approximately 7 kg in total. This power supply unit is charged via charging stations on the space station or main spacecraft - drawing power from onboard power reserves. However, due to increased radiation exposure in orbit, chemical degradation causes battery systems to lose capacity over their lifetime. By EOL (End Of Life), the LLB has 26.6 Ahr capacity with an open circuit voltage of 16-21 V [3]. Autonomy for the user is ultimately constrained by the battery capacity, in conjunction with an inherent dependency upon requiring a suitable charging system. Furthermore, a large array of electrochemical cells poses a potential fire risk from aggressive failure modes, such as thermal runaway, a negative consequence of high energy density. An intrinsic thermal

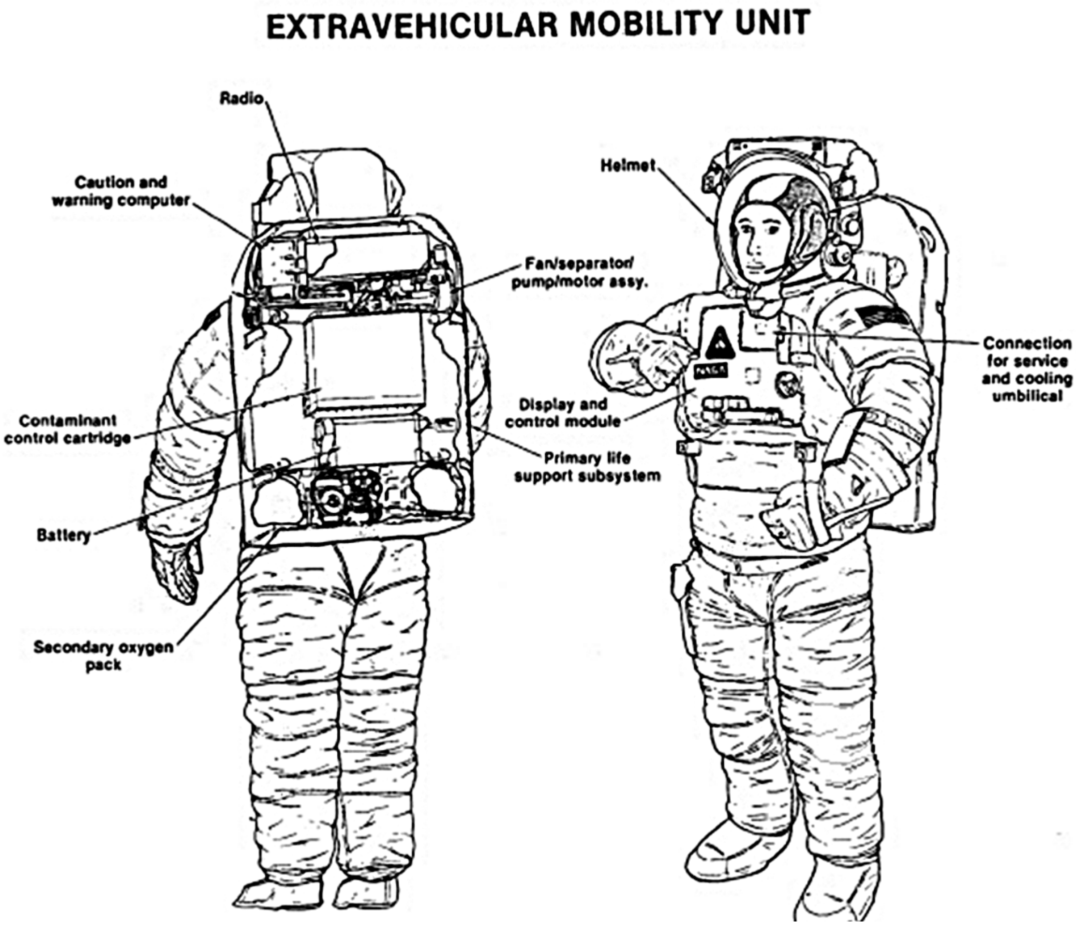

FIGURE 1.3: NASA inforgraphic showing annotated diagram of a Extravehicular Mobility Unit [3].

instability at high temperatures can lead to ignition of the venting electrolyte, in the form of smoke or fire [8]. Obviously, this risk must be driven to a minimum through rigorous research, screening and testing, in order to avoid the catastrophic event of a fire onboard a spacecraft or EMU. Although batteries are adequate for use in space, the aforementioned restrictions and risks, alongside a need for greater EVA capabilities, supports the validity of exploration into new and innovative power solutions to support EVA activity.

Advancing EVA suit design with novel and emerging technologies may prove greatly useful in increasing capabilities of space travelers when executing EVA operations. One such candidate technological innovation is the thermoelectric generator (TEG). Thermoelectric generators (TEGs), specifically flexible designs (f-TEGs), are a rapidly maturing technology - currently being developed for wearable devices, mainly within the field of medical science, and therefore exhibit potential application for EVA suits. Breakthroughs being made in this field suggest that TEGs could provide power to EVA suit systems through large and ubiquitous thermal gradients, inherited from the extreme thermal environment in space. By themselves, f-TEGs typically produce small amounts of power (O $\sim \mu W$), and so have to be connected in arrays to achieve useful output levels. In this very early stage of research, it may be more realistic to propose TEGs as a supplementary power supply for EVA activity. Although these strong thermal gradients would boost f-TEG output to levels not achievable in other applications. EVA suits could potentially harness the thermal gradient between the astronaut's body heat and the extreme thermal environment of space, advancing designs into a new generation. In addition, this technology may naturally offer an alternative power supply, perhaps auxiliary at first, that eases some of the restriction placed upon EVA by batteries. For example, the TEG is likely to constantly produce a voltage due to significant thermal gradients being ubiquitous in space - whether they be negative or positive in relation to the body's external temperature. Feeding batteries with this constant power supply may reduce dependency on charging and the EVA suit's capacity for autonomy will likely increase. Moreover, if TEG output becomes reliable enough, battery packs would shrink, leading to a reduction in weight. This would allow for greater mobility and range if used on the surface of celestial bodies, such as The Moon or Mars. With regards to operation, TEGs are purely thermoelectric, meaning no chemicals are present and so are unaffected by chemical degradation that decrease power capacity of batteries. Yet, the effects of radiation and other factors present in the extraterrestrial environment on the TEG are unknown; further experimental data will be necessary to gain insight.

Thermoelectric generators have the potential of providing power to EVA suits by harnessing the extreme thermal environment and generating bio-thermoelectric energy - offering support to current battery power supplies, and potential future alternatives. Even producing partial power from these devices could reduce battery sizes, and in turn, payload mass, whilst potentially increasing autonomy of EVA Suit users. Therefore, TEGs may offer advancements in the designs of the equipment enabling human action in space, in line with the development of infrastructure and mission sophistication in orbit, and beyond. This paper attempts to provide early preliminary assessment of this novel power solution by offering a suitable experimental design for a CubeSat mission to LEO and producing subsequent simulative results, describing expected thermal/electrical behaviours.

In order to assess whether TEGs are suitable for use in space, the device must placed in orbit and studied whilst operating. Effective experimental investigations would ideally expose the TEG to the environmental characteristics of Low Earth Orbit (LEO), such as, micro-gravity, vacuum, solar and planetary thermal loads, radiation and high energy charged particles. The comments offered by this work, for potential effectiveness, are limited by the lack of experimental data gathered. Any conclusions are drawn from the results of sophisticated modelling and simulations, without supplementary real-world data, placing constraints on the implications of this research. However, this work does attempt to build reliable models and simulated data, forming the basis for any future

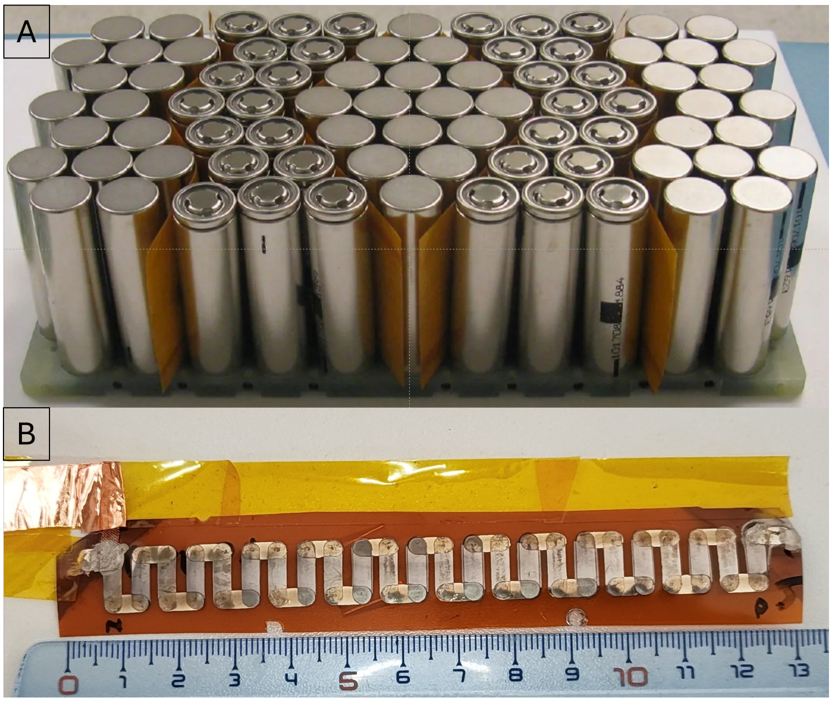

FIGURE 1.4: a) NASA EMU LLB battery pack consisting of eighty electrochemical cells in a 5S 16P configuration. b) Thermoelectric generator manufactured at the University of Southampton using sputtered deposition techniques.

experimental investigations. A pilot case study proposes an experimental design for future tests, aimed at gaining insight into the performance of TEGs in a representative environment. Subsequent simulations of this experimental design show resulting temperature gradients and electric potential that may be expected, therefore presenting a novel investigation into the effectiveness of this technology when operating within the extreme thermal environment of Low Earth Orbit (LEO).

The following work is divided into six chapters. Chapter two provides the reader some background information and history regarding EVA suits, physical processes and current technological landscape of thermoelectric generators, as well as, outlining the important contributing factors to the thermal environment of LEO. Chapter three describes and justifies the methods undertaken for designing and setting up the finite element analysis (FEA) models used to produce the results of the simulations presented in chapter four. The discussion and relevant conclusions are subsequently laid out in chapters five and six, respectively. After which, there are references for the sources used, formatted using IEEE. Next, the objectives of this investigation are listed, after which, chapter one will conclude.

1.1 Objectives

The following objectives for this investigation have been set out below using the SMART format (Specific, Measurable, Achievable, Relevant, Time-bound):

- Propose experimental design for testing thermoelectric generator operation in orbit.
- Characterise thermal and electrical behaviour of thermoelectric generator in a representative thermal environment of Low Earth Orbit.
- Measure and plot data of temperature and electric potential values over the thermoelectric generator throughout one orbit, using orbital parameters of the ISS.
- Use COMSOL Multiphysics for FEA analysis.
- Use results from models to assess potential effectiveness of technology use in space.
- Complete investigation by September.

Chapter 2

Background

2.1 EVA Suits

An Extravehicular Activity (EVA) suit or the Extravehicular Mobility Unit (EMU) is used by an astronaut when operating outside of a spacecraft - usually whilst orbiting Earth, or upon another celestial body's surface. Providing critical life support and communication for the astronaut inside, EVA suit design is greatly important for ensuring paramount protection from the vacuum of space, as well as enabling operational functionality.

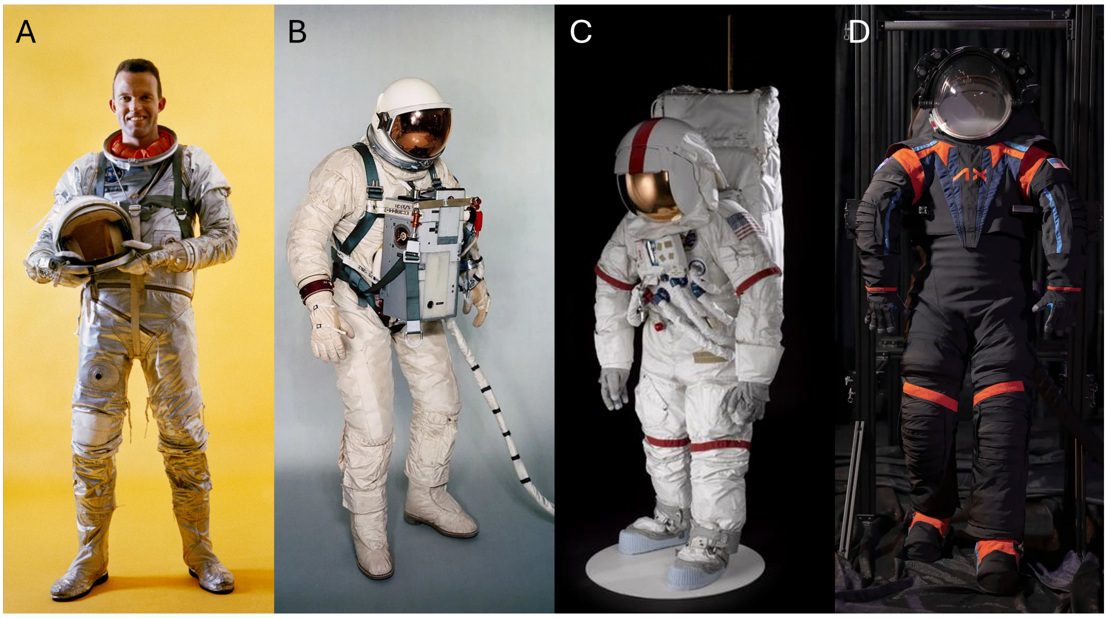

FIGURE 2.1: Compilation of NASA EVA suits from Mercury to Artemis missions highlighting the evolution of suit design. Mercury MA-9 = A [4], Gemini 4 = B [5], Apollo 17 = C [6], Artemis 3 = D [7].

TABLE 2.1: Comparison of EVA suits features and capabilities. See fig 2.1. Mercury MA-9 = A, Gemini 4 = B, Apollo 17 = C, Artemis 3 = D.

	A	B	C	D
EVA Capability [19]	X	✓	✓	✓
Umbilical Cord [19], [22]	N/A	✓	X	X
Mobility [19], [23]	Moderate	Limited	Moderate	High
EVA Duration [24], [25], [26]	N/A	20-30 min	7-8 hr	8 hr (est.)
Weight on Earth (kg) [19], [26]	10	15	90	40-50 (est.)

Early spacesuit developments built upon pressure suits used for high altitude flights in aircraft and were relatively simple due to the lack of knowledge about the space environment. NASA's Project Gemini was the first mission that allowed for spacewalks to be conducted because of the successful development of life support systems. For example, air was supplied to the astronauts via an umbilical cord; connecting the astronaut to the spacecraft and on-board oxygen supplies. Although, thermal regulation and internal humidity were not sufficiently controlled, causing fog to form on the visor and severe fatigue from overheating. These issues were resolved for the spacesuit used on the Apollo Lunar Missions, where astronauts enjoyed full autonomy from the Lunar Lander, due to life support systems being contained in a backpack, in addition to a liquid cooling system being implemented [27]. The current AxEMU spacesuit in development at Axiom Space, for the NASA Artemis III mission, aims to facilitate the next successful humans walking on the Lunar surface through the iteration of innovative design [28] . The crucial systems needed for any EVA suit include, but are not limited to, Life Support, CO2 scrubbing, Communication, Control Interface, Biometric Monitoring, Variable Suit Pressure and Lights. Exhaustive technical details of EVA suits are not available to the public due to the classified nature of the work.

FIGURE 2.2: Astronaut performing Extra-Vehicular Activity with battery usage annotated [8].

When considering alternative power supplies to a system, the up-to-date power rating required by that system must be identified. By observing data published by NASA within the last 15 years, a rough estimate can be obtained for the power supplied to EVA suits used over that period. Recent data is difficult to find as it is often classified and so my estimates for power supply capabilities will use data from 2010-2015. From this time period onward, lithium-ion batteries were adopted for EVA power supply, and most likely still are used today. These batteries supplied 40 Ahr (BOL) and 26.6 Ahr (EOL) at 16-21 Volts, supporting transient pulses every hour to handle pump and fan operation within the PLSS (Portable Life Support System) [29], [3]. Maximum duration of a single spacewalk is eight hours - a significant factor being fatigue of the astronaut. It is unlikely that eight hours of EVA activity would fully deplete the battery pack, however due to the current standard EVA suit power consumption being unknown, I will work off of this assumption. Based on these figures, the battery produces an average power rate of approximately 68 Watts over the eight hour period, at end of life. Reasonably, there may have been some improvements in efficiency in the last decade, since this data was published, which may reduce power consumption in the AxEMU. However, due to that information not being available to the public, I am unable to present any findings. Therefore, an average power consumption estimation is 68 Watts, to support EVA suit systems function. This figure could be up to 100 Watts if fully depleted at BOL. These figures give an approximate range of what would be expected from an alternative power supply. Crucially in this investigation, these power values will be used to assess potential future capabilities of TEGs for this application.

2.2 Thermoelectric Generation

Generating electrical energy from a thermal gradient is the underlying concept of thermoelectric generation. The supporting physics is contained within a phenomenon named the Seebeck Effect which can be seen when a thermal gradient is created over two connected materials. Semiconductors are widely used today, usually referred to as p-type and n-type materials, which together form a p-n junction. The thermal gradient between the two materials influences the charge carriers to diffuse into areas of lower density, initiating an electromotive force – a voltage. The relationship between thermal gradient and voltage is determined by the intrinsic properties of the materials in use and is quantified, at discrete operating temperatures, by the Seebeck coefficient, $\alpha = V/\Delta T$.

Additional useful parameters for measuring the performance of ideal TE devices can be estimated using the following expressions for maximum heat-to-power conversion efficiency η_{max} and output power density ω_{max}.

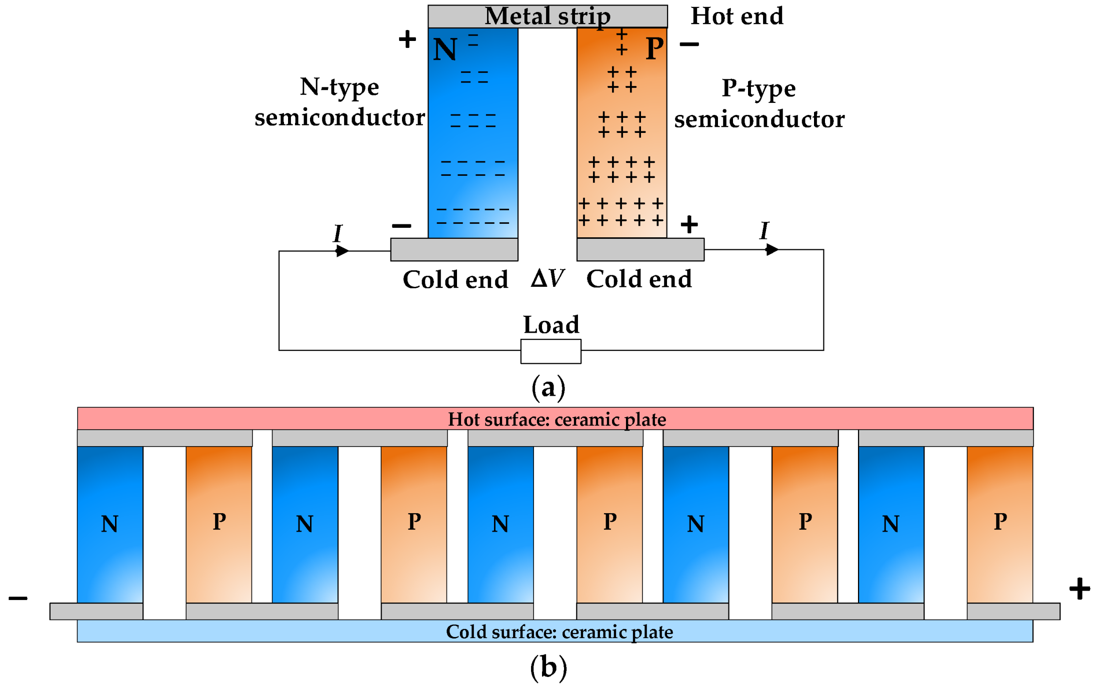

FIGURE 2.3: Diagram showing: a) Underlying physics of a thermoelectric generator leg pair b) Collection of thermoelectric generator legs constituting a TEG [9].

$$\eta_{max} = \frac{(T_H - T_C)}{T_H} \frac{\sqrt{(1 + \overline{ZT}} - 1}{\sqrt{(1 + \overline{ZT}} + \frac{T_C}{T_H}}$$

$$\omega_{max} = \frac{(T_H - T_C)^2}{4L}\overline{\alpha^2\sigma}$$

T_H and T_C are the hot and cold side temperatures of the TEG leg, respectively. L is the length of the leg, α is the Seebeck coefficient and σ is the electrical conductivity. The ZT term is a dimensionless figure of merit for thermoelectric devices and is defined as,

$$ZT = \frac{\alpha^2}{RK}T$$

Where R, K and T are electrical resistance, thermal conductance and absolute temperature. Therefore, $\overline{ZT}$ is the average value between the two sides of the leg; indicating the device's ability to generate power/cool.

Up until relatively recently, thermoelectric technology has only been used in niche applications in industry because of intrinsically poor efficiency. Even so, it found use in applications where reliability outweighed performance. For example, the Radioisotope Thermoelectric Generator (RTG) has been used for space missions such as Apollo, Voyager and Perseverance, to name only a few. These systems are highly reliable, with long lifetimes, generating in the order of 100 Watts [30]. However, they are large, heavy and potentially hazardous, leading to their inadequacy for EVA suits and so have remained only being used for these highly specialised missions.

Advancements in material science have consequently enabled more effective thermoelectric generators (TEGs) to be engineered. With smaller and more sophisticated thermoelectric (TE) devices being built, applications are beginning to spread into increasingly novel areas.

Bulk TE devices are commonly used in industry for heat energy recovery as they produce the most amount of power at high temperatures and are composed of typical Bismuth-Telluride (Bi2Te3) p-type and n-type semiconductor junctions [31]. On the other hand, micro-TEGs are developed for small, flexible systems and come in many different forms. Fiber-based TEGs can be woven in textiles and are made from inorganic fibers such as Skutterudite, or organic fibers such as Polyalinine [32]. Gomez et al. [33] demonstrated thermoelectric textiles via electrochemical polymerization of poly(3,4-ethylenedioxythiophene) (PEDOT) on felt fabrics, achieving a 6.5 µW power output. Thin-film TEGs can be integrated into micro-electronics, using materials such as Ag2Se (Silver Selene) to achieve good power outputs at small scale [34], [35]. Flexible TEGs (f-TEGs) can even be printed using inkjet, yielding low cost and potentially large-scale manufacturing capabilities [36], [37].

In the field of medical science, there has been great interest and development of devices that are powered via wearable TEGs – using the thermal difference between the human skin and ambient temperature. Wearable TEGs produce power at the microwatt level, utilising a thermal gradient between body heat and ambient temperature. These so called, "Self-powered", medical devices have been demonstrated to successfully operate to measure vital signs such as ECG and oxygen levels [38], [39]. This successful example of TEGs being utilised at a small scale to produce usable levels of power prove that this technology is becoming suitable for real-world use. For an EVA suit, an f-TEG would be required as flexibility of the suit is critical for astronaut movement.

Morgan et al. used physical vapour deposition as an alternative manufacturing method – producing an f-TEG exhibiting a Seebeck coefficient of 140 µV/K and 0.4 nW per pair. When used in conjunction with an AEM2094 energy harvester and a Bluetooth device, an array of sixteen f-TEGs were connected in series, each under a 24K temperature gradient. This configuration was able to produce 13.6 µW, charging a 6600 μF capacitor, ultimately transmitting sensor values at 25-minute intervals [40], [10]. Importantly, the investigation used an f-TEG design with an optimum leg length of 6 mm. For simplicity, I have used a leg length of 12 mm in FEA modelling. This particular f-TEG will be the subject of my pilot case study and will be evaluated within a representative thermal environment.

Bell outlined that devices must exceed a ZT value of 1.5 to be effective power production devices [41], however the significance of this metric seems to be questionable since novel TEGs routinely attain high power densities without fulfilling Bell's criterion [42]. Miao et al. [43] achieved good maximum power output of 18 $\mu Wcm^{-}2$ with a ZT value of only 0.75, at room temperature. However, this increased drastically to 900 $\mu Wcm^{-}2$ when the temperature difference was increased to 40K, highlighting the potential for utilising large thermal gradients in extreme environments, such as space.

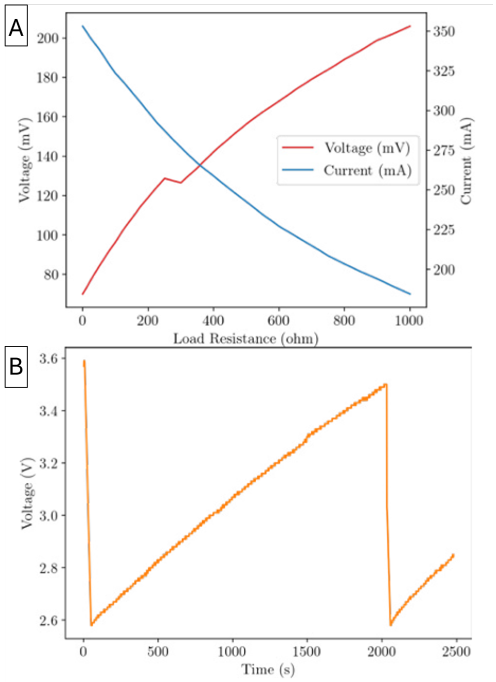

FIGURE 2.4: a) Sixteen f-TEG array output over various resistances at $\Delta T = 24K$. b) Capacitor voltage showing charging by f-TEG array [10].

ZT only indicates the capacity of the materials in use but there are many other factors that affect the final energy harvesting ability, such as device architecture, manufacturing processes, conductor material and quality and environment. Another important consideration is durability. Thermal cycling induces stresses in the materials and solder layer between semiconductors and conductors, eventually propagating micro-cracks, leading to an increased internal resistance and decreased power output. Effectively, this process decreases ZT of the materials. Also, faster thermal cycling exacerbates the rate of ZT degradation. Marienne et al. [44] showed that ZT decreases by 39% after 600 cycles at a frequency of 720s. For less frequent thermal cycling to reflect an orbital period, with period $t = 5400s$, a lower degradation will be expected. Wang et al. [45] produced a mathematical model to predict lifetime of TEGs over N cycles. Furthermore, for flexible thermoelectric generators (f-TEGs), there will be a detrimental effect via mechanical stresses, referred to as bending cycles. These bending cycles function similarly to the thermal cycles by increasing internal resistance due to micro crack propagation. Novel manufacturing processes can minimise these effects in f-TEGs. Ding et al. [46] managed to produce a flexible TEG capable of withstanding at least 10^6 bends at 3mm radius via a facile hot-rolling technique. Although the combined effects of thermal and bending cycles will most likely cause an increased propagation of micro cracks, it is unclear the extent of this due to lack of lifetime models produced with both cycles in mind. Ren et al. [47] have exhibited a TEG with self-healing properties by using liquid metal for the conductors. This type of innovation may extend lifetimes of f-TEGs greatly and lessen the detrimental effect of thermal and bending cycles on performance.

The challenge in employing TEG technology to power a sophisticated EVA suit mainly lies in the sheer amount of power required, among other practical issues. To implement f-TEGs to power a suite of sub-systems, requiring up to 100 Watts, the effective power output will need to be vastly increased compared to typical uses. Realistically, this technology can aim at supplementing the battery power supply by producing some auxiliary power, providing an increase in electrical power output, assisted by the extreme temperatures apparent in space.

2.3 Orbital Thermal Environment

As TEGs are reliant upon a thermal gradient to generate electricity; the characteristics of the thermal environment that EVA suits operate in are of central concern to this study. Currently, spacewalks occur entirely within Low Earth Orbit (LEO) and so it is logical to take the representative thermal environment to be that of the International Space Station (ISS): the site of most EVAs. This is defined as a circular orbit at 400km altitude with the following keplerian orbital elements [48]:

- Orbital Radius = 6771 km
- Eccentricity = 0
- Inclination= 51.6°
- Right Ascension of Asccending Node = 0 to 360°
- Argument of Periapsis = 0 to 180°
- Mean anomaly = 78°

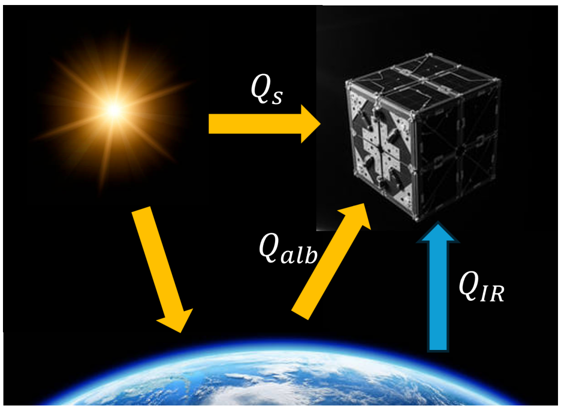

FIGURE 2.5: Diagram of sources of heat experienced by a spacecraft (or any object) in orbit around Earth.

At this defined orbit, the three contributors to the thermal environment are: direct solar radiation, albedo and infrared. Direct solar radiation (Q_s) is the dominant contributor but will vary slightly depending on where the Earth is on its slightly eccentric orbit. Albedo (Q_{alb}) is simply how much solar radiation is reflected by the Earth and consequently absorbed by objects in orbit. Lastly, the solar radiation absorbed and emitted by the Earth as infrared energy (Q_{IR}) will comprise the final contributor to the LEO thermal environment. Salazar-Salinas et al. [49] outlined the maximum and minimum values for an ISS orbit environment, corresponding to the perihelion and aphelion of Earth, for a 1U CubeSat.

Heat energy absorbed from direct solar radiation is calculated by:

$$Q_S = \alpha G_s A \cos\theta$$

where α, G_s, A and θ are the absorptance of the surface, solar flux incident to the perpendicular plane, the surface area and the angle of incident rays. Heat energy absorbed from the Earth's reflected light or albedo is calculated by:

$$Q_{alb} = \alpha G_s A F_{s-p} a \cos\phi$$

where F_{s-p}, a and ϕ are the view factor from the surface to Earth, albedo factor and angle of incident rays. Heat energy absorbed from infrared radiation of the Earth is calculated by:

$$Q_{IR} = \epsilon q_{ir} A F_{s-p}$$

where ϵ and q_{ir} are the emissivity of the surface and the infrared flux at the surface.

TABLE 2.2: Minimum and maximum values of heat sources for a spacecraft in LEO (400km altitude). Q_S = Direct Solar Radiation, Q_{alb} = Albedo, Q_{IR} = Infrared.

	Aphelion	Perihelion
$Q_s\ (W/m^2)$	1323	1414
Q_{alb}	0.25	0.5
$Q_{IR}\ (W/m^2)$	220	275

The values listed in Table 2.2 will vary depending on critical material values such as absorptance and emissivity, in conjunction with situational parameters such as, view factors and surface area. Interestingly, absorptance appears in the two strongest contributors making it a good candidate for a parameter study.

Additionally, heating will cease once the orbiting object enters the eclipse side of the Earth - lasting for approximately a third of the orbital period. In the absence of incident radiation to increase temperatures, objects will emit thermal energy as EM waves into space. Approximately, this results in a thermal cycle of 60 minutes of heating, followed by 30 minutes of cooling, which forms the basis for thermal environment.

Chapter 3

Methods

3.1 COMSOL Simulation

With the goal of outlining how a TEG may behave in LEO, simulations performed using COMSOL Multiphysics obtained voltage and temperature plots when under orbital thermal loads. First, the FEA model for the TEG was created to reflect the real-life device. Then, the preliminary model was designed in order to create an approximate CubeSat system with a payload that would behave similarly to the real TEG. This model was highly useful in gaining early insight into the thermal behaviour of the system, allowing for quick adjustment of materials and geometries with light computational resources. Once a complete preliminary model had been created and validated using simulations, it was used as a basis for a more sophisticated model, using an imported 3D CAD model of a 1U CubeSat. I refer to this model as the 1U CubeSat Model. Finally, the TEG and 1U CubeSat Model were integrated together, forming the final form of my proposed experimental configuration - referred to as the Combined Model.

Considering that a future stage of research for this technology would be to place the TEG in orbit around Earth, inside a spacecraft, and collect data to see how it behaves in this novel environment, the simulation space was built to reflect this scenario. Firstly, a 1U CubeSat seemed most sensible as it could be scaled up to whatever size needed. Secondly, a parameter study was performed on the Combined Model by varying the absorptance (α) of the exterior faces of the CubeSat via thermal paint materials. These three materials all have high emissivity ($\epsilon \simeq 0.9$) and varying absorptances ($\alpha = 0.2, 0.55, 0.9$). The low and high values were taken from white (S13G/LO-1) [50] and black (Z306) [51] thermal paints used for passive thermal control on CubeSat missions, and a midpoint was created to provide a reasonable range. With this, a range of expected thermal behaviours could be determined, accommodating many CubeSat design options. Gathering data from all three of these scenarios would give two extremes and a midpoint to indicate how different surface properties would affect the overall system.

3.2 Thermoelectric Generator Model

This case study is concerned with a specific thermoelectric generator fabricated using sputtered deposition techniques at the University of Southampton. Schematics and information regarding the design of this device were received from Dr Katrina Morgan from the department of Electrical Engineering. Due to the nanoscopic nature of some elements of the TEG, it became necessary to simplify the model to make it suitable for finite element analysis, and so appropriate measures were taken in collaboration with Dr Katrina Morgan to make it so.

3.2.1 Design and Material Selection

The TEG design is represented within the COMSOL model as close as possible to the real device. Steps taken to simplify the model enabled analysis using FEA whilst yielding a faithful model that would produce useful data. Firstly, the thickness of the TEG legs and contacts have been increased in the model so that effective meshing can be achieved. The Ti/Ag/Ti structure of the contacts has been simplified to one layer of silver as the thickness of the titanium layers were of the order of nanometers. Moreover, the layer of silver has been increased in thickness from 500nm to 5 μm to match the thickness of the TEG legs - ensuring successful meshing between boundaries of the same thickness.

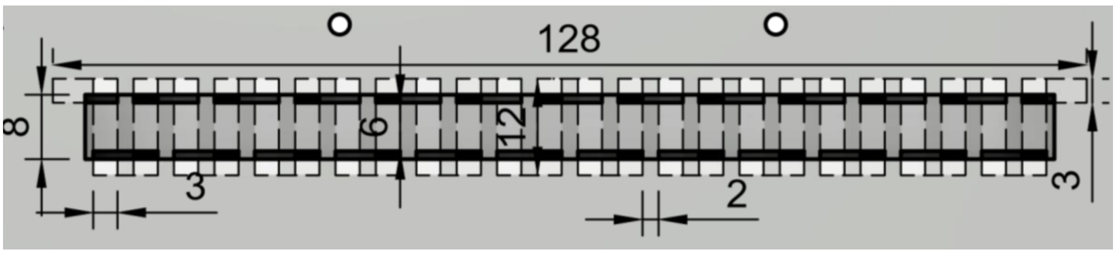

FIGURE 3.1: Schematic of TEG design. Measured in microns.

The grey rectangle with black outline seen in the schematic represents SiO2 capping and has been omitted for simplicity. Also, the schematic does not show the Polyimide substrate on which the TEG is deposited.

Constructing the TEG with the aforementioned geometries resulted in a model largely representative of the real-life device, with ten TEG P-N legs pairs. Considering that this TEG will eventually have to fit inside a 1U CubeSat model, it became necessary to shorten this model to 60 mm in length. 60 mm was specifically chosen because it is

TABLE 3.1: Geometry and material composition of the TEG model within COMSOL Multiphysics.

Element	Dimensions (w x h x d) mm	Material
Substrate	120 x 14 x 0.127	Polyimide (Kapton)
TEG Legs (P-Type)	3 x 12 x 0.005	Antimony Telluride (Sb2Te3)
TEG Legs (N-Type)	3 x 12 x 0.005	Bismuth Telluride (Bi2Te3)
Contacts	8 x 3 x 0.005	Silver (Ag)

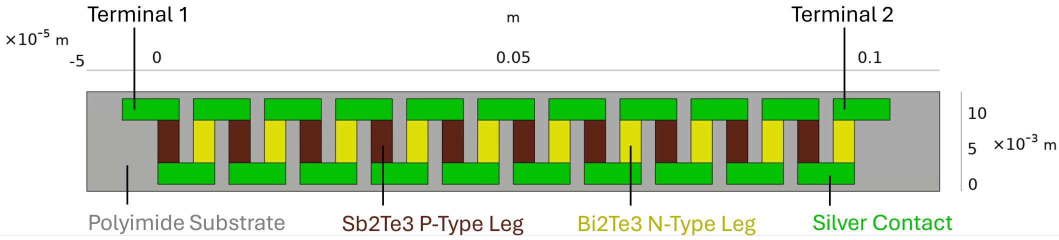

FIGURE 3.2: Full-sized (L=120 mm) TEG Model within COMSOL Multiphysics.

the largest size that would fit into the final models, therefore maximising the voltage being generated. Simply, the number of leg pairs was decreased to from ten to five and the Polyimide substrate shortened to 60 mm, to accommodate the smaller model. This model underwent verification by measured electric potential over the entire device whilst experiencing a temperature difference between the two rows of contacts.

3.2.2 Simulation Physics Settings

Voltage generation within a TEG relies upon the Thermoelectric Effect and temperature gradients present. Successfully verifying this TEG model within COMSOL Multiphysics required using the following physics modules: Heat Transfer in Solids (ht), Electric current (ec), Electrical Circuit (cir), as well as, Electromagnetic Heating (emh) and Thermoelectric Effect (tee), for the Multiphysics Coupled Interfaces.

The temperature gradient created, via two temperature nodes under the Heat Transfer in Solids module, formed the basis for evaluating the magnitude of voltage generation across the TEG under a 100°C gradient. These nodes set the temperature of selected object faces to a temperature, so that a stationary solver can capture a snapshot of the generated voltage under these conditions. The first temperature node included all the faces of the contacts on the ”long side” (the row with more contacts) in it’s boundary selection and set the temperature to 67°C. The second node selected all the +z face boundaries of the contacts from the ”short side” and set them to -33°C.

For the Electric Currents module, two terminal modules were assigned to the each of the contacts on either end of the TEG, respectively. Terminal 1 was set to be a voltage terminal at 0V, whereas Terminal 2 was set to be a circuit terminal and connected to the

External I vs. U node under Electrical Circuit. In addition, a resistor node was added to the Electrical Circuit module, with a resistance of 1000Ω - setting the resistance of the PN junction to a realistic value. Combined, these settings emulate an experimental environment for the TEG to operate under and consequently enable representative electrical behaviour to occur. This configuration allows a voltage to build up across the device terminals in response to the imposed thermal gradient, reproducing practical TEG operation under experimental conditions.

A physics-controlled mesh was used with a fine element sizing and all other settings were default.

3.3 Preliminary Model

A preliminary study was set up to test the validity of the proposed model by introducing a cube, with a TEG substitute connected to it's center, to external radiative sources and performing subsequent thermal analyses. The purpose of using a TEG substitute for preliminary studies was to minimise computational requirements, due to the inherent complexity of the full TEG model, whilst computing simulations to verify the temperature gradients were exhibiting as expected. The design of the preliminary model allows for thermal energy to be collected from the direct solar radiation, as well as planetary sources (albedo and infrared), by the conductive spot on the face of the CubeSat that always faces the Sun ("Hot Spot"). Thermal energy is then channeled via conductive plates ("Thermal Links") towards the TEG substitute; split into three domains to emulate the architecture of the TEG - comprising of a center section made of Bismuth Telluride, sandwiched between sections of silver, in contact with the thermal links.

3.3.1 Geometry

With a preliminary model to arrive at, the COMSOL model was verified at each key iterative stage, whereby geometries were added to the model. Firstly, applying the difference boolean operation upon a cube geometry (10 x 10 x 10 cm), with another cube (98 x 98 x 98 mm), created a 10 cm cube shell with thickness of 1 mm, filled with a finite void. The geometry was centered at the origin of the axes.

After this, two smaller blocks sized (60 x 60 x 1 mm) were placed at +4.95 cm and -4.95 cm, respectively, along the z-axis from the center of the cube shell. A side length of 60 mm was chosen to match up to the length of the TEG model. Using the difference boolean operation and keeping the objects being subtracted created the conductive spots on the cube shell frame.

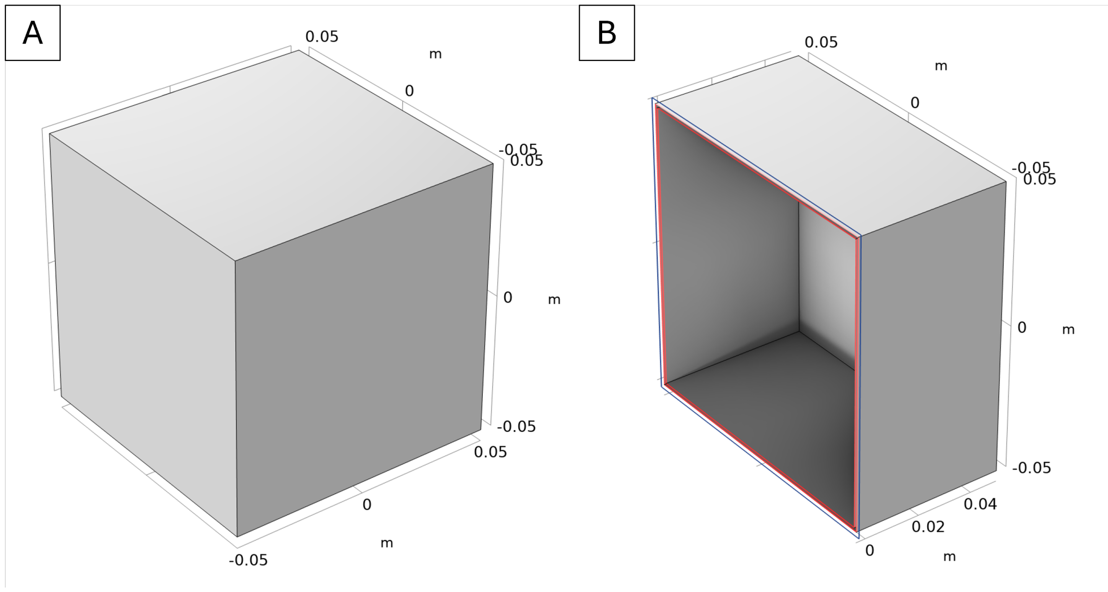

FIGURE 3.3: COMSOL Multiphysics geometry rendering of cube shell.

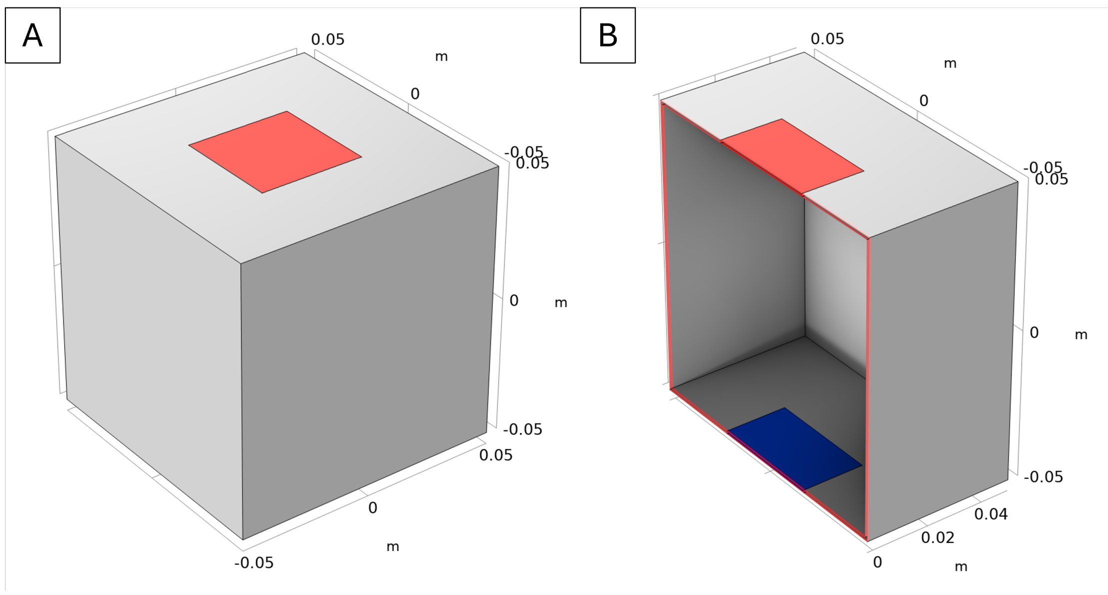

FIGURE 3.4: COMSOL Multiphysics geometry rendering of cube shell, with Cold Spot (blue) and Hot Spot (red).

The next step in the preliminary design adds thin metal plates that carry the thermal energy to the center of the model and then out again, through the conductive spots. One block sized at (60 x 100 x 1 mm) was first built into the geometry to verify the presence of crucial conduction, all the way along the block. Once verified, the block was split into two blocks, attached to either side of the structure with an empty space in the center to accommodate the TEG.

The TEG substitute was designed to produce representative thermal behaviour of the full TEG model and therefore was split into three key sections: two contacts and a central semiconductor area. The two contact lengths are analogous to the small contacts