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Analysis of thermoelectrics used in the aerospace industry for power generation by the seebeck effect

Análisis de termoeléctricos utilizados en el sector aeroespacial para la generación de energía mediante efecto seebeck

RODRIGUEZ-AVILA, Jesus*†, VALLE-HERNANDEZ, Julio and GALLARDO-VILLARREAL, José Manuel

Universidad Politécnica Metropolitana de Hidalgo
Universidad Autónoma del Estado de Hidalgo

ID 1st Author: *Jesus, Rodriguez-Avila* / **ORC ID**: 0000-0002-4124-2159, **CVU CONACYT ID**: 1148513

ID 1st Co-author: *Julio, Valle-Hernandez* / **ORC ID**: 0000-0001-8957-0066, **CVU CONACYT ID**: 210743

ID 2nd Co-author: *José Manuel, Gallardo-Villarreal* / **ORC ID**: 0000-0002-7578-7229, **CVU CONACYT ID**: 366394

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Abstract

Currently the generation of energy in space is of vital importance for research on other planets and moons, as all missions sent are powered by electricity so that they keep all their instruments operating properly and present no short-term problems. For the generation of energy outside the planet earth are presented the power converters which are able to convert thermal energy into electrical energy, currently there are two types of power converters which are dynamic and static, for this work are addressed the static, also called thermoelectric that work from a physical phenomenon called seebeck effect which USES two metals of different composition united, They take advantage of a temperature gradient where one end is kept at a hot temperature and the other at a cold temperature, causing a voltage differential. For a material to be considered thermoelectric and work properly has to have some properties such as the seebeck coefficient, electrical resistivity and thermal conductivity, in this work we study some thermoelectrics used in the aerospace sector which are Bi_2Te_3, $PbTe$, $SiGe$, Skutterudite and $BiSbTe$ Where its thermoelectric properties will be analyzed according to its operating temperature range, the merit figure zt will be calculated, the electrical power generated, the input heat and the output heat, finally a comparative table of the electrical power generated by the static converters and another of its applications in the space sector will be performed. This work provides information on the most used thermoelectrics in the space sector, as well as the physical phenomena involved in static converters.

Thermoelectric, Merit Chart, Seebeck coefficient

Resumen

Actualmente la generación de energía en el espacio es de vital importancia para la investigación en otros planetas y lunas, ya que todas las misiones enviadas son alimentadas por electricidad de forma que mantengan todos sus instrumentos operando de manera adecuada y no presente problemas a corto plazo. Para la generación de energía fuera del planeta tierra se presentan los convertidores de potencia los cuales son capaces de convertir la energía térmica en energía eléctrica, actualmente existen dos tipos de convertidores de potencia los cuales son los dinámicos y los estáticos, para este trabajo se abordan los estáticos, también llamados como termoeléctricos que funcionan a partir de un fenómeno físico llamado efecto Seebeck el cual utiliza dos metales de diferente composición unidos, estos aprovechan un gradiente de temperatura donde un extremo se mantiene a una temperatura caliente y otro a una temperatura fría, ocasionando un diferencial de voltaje. Para que un material sea considerado termoeléctrico y funcione correctamente tiene que presentar algunas propiedades como el Coeficiente de Seebeck, Resistividad Eléctrica y la Conductividad Térmica, en este trabajo se estudiaran algunos termoeléctricos utilizados en el sector aeroespacial los cuales son Bi_2Te_3, $PbTe$, $SiGe$, Skutterudite y $BiSbTe$ donde se analizara sus propiedades termoeléctricas de acuerdo a su rango de temperatura de operación, se calculara la figura de mérito ZT, la potencia eléctrica generada, el calor de entrada y el calor de salida, finalmente se realizara una tabla comparativa de la potencia eléctrica generada por los convertidores estáticos y otra de sus aplicaciones en el sector espacial. Este trabajo brinda información sobre los termoeléctricos mas utilizados en el sector espacial, así como los fenómenos físicos involucrados en los convertidores estáticos.

Termoeléctrico, Grafica de Merito, Coeficiente de Seebeck

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*Correspondence to Author (email: aracelih@icf.unam.mx)
†Researcher contributing as first Author.

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1. Introduction

Power generation for the aerospace sector is very important nowadays since it represents an important point for any mission that requires electrical power supply in order to maintain all its scientific instruments and components that help its movement through space, with the purpose of proper operation. There are several ways to generate electrical energy in space is by means of solar panels that are placed externally attached to the structure of the aircraft or deployed to collect light from the sun to later convert it into electrical energy, this process is known as photovoltaic effect.

On the other hand, the use of nuclear energy in space has been present since the last decade in missions where distances are so far away that sunlight cannot reach with the same intensity, so nuclear energy in space requires dynamic and static power converters. Static converters do not require any moving parts for their operation, these converters are also called thermoelectric, there are three types of thermoelectric effects which have various applications in the generation of electric potentials through the Seebeck effect and cooling of small volumes using the Peltier effect. These thermoelectric effects are classified into Seebeck, Peltier and Thomson effect. The Peltier effect, the opposite of the Seebeck effect, consists of supplying an electric current in an electric circuit formed by two different metals, in one of its junctions heat will be absorbed from the medium and in the other it will be given up. In this effect the ratio of current supplied for cooling is directly proportional to the temperature difference between the junctions of the two metals.

The Thomson effect is described as the absorption or generation of heat along a homogeneous electrical conductor, through which an electric current flows and with junctions at different temperatures. In other words, the heat is proportional to the electric current and the temperature gradient.

For the Seebeck effect a closed circuit composed of two different metals in contact, with junctions at different temperatures, generates an electric current which has as a consequence a magnetic field, which was detected by a galvanometer, which Seebeck had close to the circuit.

Consequently, in an open circuit, under the same conditions, an electric potential difference is generated in its junctions. The relationship between the temperature gradient and the voltage generated is direct, and is related to the proportionality constant called Seebeck's coefficient (S). The thermoelectrics to be analyzed for this work are Bi_2 Te_3, PbTe, Skutterudite, BiSbTe and SiGe, making them viable candidates for implementation in the aerospace sector.

According to the thermoelectrics proposed for this work, some properties are obtained in the form of polynomials such as Seebeck coefficient, electrical resistivity and thermal conductivity, from these properties, the input and output thermal power is calculated, then the electrical power generated by the thermoelectrics is determined with an energy balance. With the results obtained it is determined that they would have in the aerospace sector.

2. Methodology

This work has the following methodology to be developed:

- Thermoelectric by Seebeck effect.
- Polynomials for thermoelectric types by Seebeck effect.
- Calculate the Seebeck coefficient, electrical resistivity and thermal conductivity as a function of thermoelectric temperature ranges.
- Calculate the electrical power generated by each type of thermoelectric power plant.
- Seebeck effect thermoelectrics applications in space.

3. Development

In the following section the development for the analysis of the different thermoelectrics used in the space sector is carried out. For this purpose, a search for the best thermoelectrics with the best properties such as Seebeck Coefficient, electrical resistivity and thermal conductivity was carried out in order to analyze them separately according to their operating temperature range.

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3.1. Static Power Converters

Thermoelectric generators are solid-state devices with no moving parts, reliable and scalable solid-state devices, which are ideal for small-quantity power generation and energy harvesting. Thermoelectric generators (TEGs), known as solid-state devices, are used to generate electrical power from a temperature gradient. TEGs are small in size and maintenance-free.

To generate electricity through the thermoelectric effect, a thermoelectric module and a temperature difference between the two sides of the module are required. Since current circulation also generates heat migration, the hot and cold sources must continuously contribute and dissipate heat to maintain this difference. A thermoelectric module generally consists of three to 127 pairs; the pairs are connected together electrically in series and thermally in parallel to form the device.

The thermoelectric system is composed of modules of different semiconductor materials because the performance changes with operating temperature.

The materials selected for the thermoelectric system are Bismuth Telluride (Bi_2 T_3), Lead Telluride (PbTe), Silicon Germanium (SiGe), Bismuth Antimony Telluride (BiSbTe) and Skutterudite. Thermoelectrics have different temperature ranges, which are described as follows.

Static Power Converters	
Thermoelectric	Operating Temperature Range
Bismuth Telluride	300 a 570 K
Lead Telluride	500 a 800 K
Silicon Germanium	750 a 1000 K
Skutterudite	273 a 773 K
Bismuth Telluride Antimony	273 a 773 K

Table 1 Temperature Range Thermoelectrics

Due to their composition and temperature range, they present significant changes in some thermal and electrical properties in some thermal and electrical properties.

The efficiency of thermoelectric devices is very strongly associated with a figure of merit dimension in Eq.1.

$$ZT = \frac{S^2\sigma}{k}T \qquad (1)$$

Where:

ZT = Figure of merit.
S = Coeficiente de Seebeck $\left[\frac{V}{K}\right]$.
σ = Electrical Conductivity $\left[\frac{1}{\Omega m}\right]$.
k = Thermal conductivity $\left[\frac{W}{mK}\right]$.
T = Absolute temperature $[K]$.

The ZT figure is also a convenient indicator for the evaluation of the potential efficiency of thermoelectric devices: a good thermoelectric material has, in general, a ZT value close to unity. Static power converters usually have a low efficiency.

3.2 Thermoelectric Properties

In order to calculate the electrical power generated, it is necessary to know the thermoelectric properties, which are as follows:

Seebeck coefficient (S, $\left[\frac{V}{K}\right]$).
- Electrical Resistivity (ρ, $[\Omega m]$).
- Electrical Conductivity (k, $\left[\frac{W}{mK}\right]$).
- Electrical Resistance ($R, [\Omega]$)
- Electric Current ($I, [A]$).

Bismuth telluride has a low temperature range compared to the other selected thermoelectrics so the values corresponding to the Seebeck coefficient, thermal conductivity and electrical conductivity are taken by means of the following polynomials obtained from the experimental values of reference [III][IV]. The polynomial of the Seebeck coefficient and the electrical resistivity (ρ) of the thermoelectric Bi_2 Te_3 is a function of the temperature range to determine it, it is necessary to take the temperature in Kelvin from 300K to 570K, which is expressed in the following polynomials la Ec.2 y Ec.3.

$$S(T_s) = -1.9 * 10^{-6}T_s^5 - 0.12 * 10^{-6}T_s^4 + 4.1 * 10^{-6}T_s^3 - 3.4 * 10^{-6}T_s^2 + 11 * 10^{-6}T_s + 1.5 * 10^{-6} \qquad (2)$$

$$\rho(T_\rho) = 2.5 * 10^{-7}{T_\rho}^2 + 2.7 * 10^{-6}T_\rho + 4.1 * 10^{-5} \qquad (3)$$

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Where the value of z is expressed as the Ec.4.

$$T_s = T_\rho = \frac{T - 4.1*10^2}{76} \quad (4)$$

In this case the thermal conductivity remains constant for the temperature range used, around 0.85 W/(m*K) [III]. For the PbTe material according to a temperature range from 500K to 800K, the following polynomials of experimental values were obtained from the reference [III][V].

$$S(T_s) = -8.2*10^{-6}T_s^{\,4} - 7.3*10^{-6}T_s^{\,3} - 7.9*10^{-6}T_s^{\,2} + 54*10^{-6}T_s + 2.8*10^{-4} \quad (5)$$

$$\rho(T_\rho) = 6.4*10^{-5}T_\rho + 5.5*10^{-5} \quad (6)$$

$$k(T_k) = 0.23*T_k^{\,2} - 0.28*T_k + 1.2 \quad (7)$$

Where the values of T_s,T_ρ and T_k are expressed in the following equations:

$$T_s = \frac{T - 5.3*10^2}{150} \quad (8)$$

$$T_\rho = \frac{T - 5.3*10^2}{350} \quad (9)$$

$$T_k = \frac{T - 5.3*10^2}{170} \quad (10)$$

For the SiGe thermoelectric, which is in the higher operating temperature range from 750K to 1000K, the polynomials corresponding to its properties are expressed according to experimental values from the references [III][VI].

$$S(T_s) = -4.5*10^{-6}T_s^{\,3} - 9.6*10^{-6}T_s^{\,2} + 6*10^{-5}T_s + 0.0002 \quad (11)$$

$$\rho(T_\rho) = 1/(8.7*10^3T_\rho^{\,2} - 2.5*10^4T_\rho + 6.7*10^4) \quad (12)$$

Where the values for T_s y T_ρ are expressed in the following equations:

$$T_s = \frac{T - 6.5*10^2}{240} \quad (13)$$

$$T_\rho = \frac{T - 6.5*10^2}{240} \quad (14)$$

The thermal conductivity of SiGe over the temperature range used is practically constant, $4.5\frac{W}{m*K}$[III].

The thermoelectric properties of Skutterudite are given in the form of a polynomial, taking into account that the temperature must be in degrees Celsius. [VI][VII]. The polynomials obtained are as follows.

$$S(T_s) = -1.06*10^{-4} - 2.92*10^{-7}T_s + 2.24*10^{-10}T_s^{\,2} \quad (15)$$

$$\rho(T_\rho) = 3.25*10^{-6} - 5.19*10^{-9}T_\rho - 2.61*10^{-12}T_\rho^{\,2} \quad (16)$$

$$k(T_k) = 5.53 - 0.009T_k - 2.45*10^{-5}T_k^{\,2} + 3.99*10^{-7}T_k^{\,3} + 1.05*10^{-9}T_k^{\,4} - 1.4*10^{-11}T_k^{\,5} + 1.04*10^{-14}T_k^{\,6} + 1.36*10^{-16}T_k^{\,7} - 3.66*10^{-19}T_k^{\,8} + 2.74*10^{-22}T_k^{\,9} \quad (17)$$

For the thermal conductivity, a ninth degree polynomial has been used, where the temperature T is given in °C.

$$T_s = T_k = T_\rho = T \quad (18)$$

On the other hand, the thermoelectric properties of BiSbTe have been obtained from reference [VI][VII], and therefore the following polynomials are obtained.

$$S(T_s) = 1.72*10^{-4} + 5.88*10^{-7}T_s - 1.87*10^{-9}T_s^{\,2} \quad (19)$$

$$\rho(T_\rho) = 6.65*10^{-6} + 4.92*10^{-8}T_\rho + 3.14*10^{-11}T_\rho^{\,2} \quad (20)$$

$$k(T_k) = 1.21 - 3.71*10^{-3}T_k + 1.60*10^{-5}T_k^{\,2} \quad (21)$$

Where the temperature is used according to its operating range in degrees Celsius.

With the Seebeck coefficient (S) of each of the thermoelectrics, the voltage produced is obtained according to the temperature range of each thermoelectric and a temperature on the cold side.

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The temperature on the cold side is affected by the hot side, as well as the cooling or dissipation systems in which the phenomena of natural or forced convection and radiation are involved, for this work a temperature is set on the cold side for each of the thermoelectrics. The voltage produced by the semiconductors is obtained according to the principle of the Seebeck effect shown in the Ec.22.

$$\mathrm{V} = \mathrm{S}(T_\mathrm{c} - T_f) \quad (22)$$

Where:

V = Voltage $[V]$.
S = Seebeck Coefficient $\left[\frac{V}{K}\right]$.
T_c = Temperature on the hot face $[K]$.
T_f = Cold face temperature $[K]$.

The electrical resistance of the thermoelectrics is determined with the Ec.23.

$$\mathrm{R} = \rho\frac{e}{A} \quad (23)$$

Where:

ρ = Electrical Resistivity $[\Omega * m]$.
e = Thermoelectric thickness $[m]$.
A = Thermoelectric Area $[m^2]$.

The electrical power generated is calculated by means of the Ec.24.

$$\mathrm{P} = \mathrm{SI}(\mathrm{T_c} - T_f) - RI^2 \quad (24)$$

To obtain the maximum current, the electrical power is partially derived with respect to the current and equaled to zero as shown in the Ec.25.

$$\frac{\partial \mathrm{P}}{\partial \mathrm{I}} = 0 = \mathrm{S}(\mathrm{T_c} - T_f) - 2RI \quad (25)$$

With the voltage and resistance calculated according to the temperature range of each of the thermoelectrics, the calculation of the maximum electric current is carried out by means of the Ec. 26.

$$I_{max} = \frac{\mathrm{V}}{2R} \quad (26)$$

The calculation of the electrical power generated by thermoelectrics according to their respective temperature ranges, allows to understand which could be their possible applications.

3.3. Electrical Power Calculation

To determine the electrical power generated by thermoelectrics from the input heat (Q_ent), on the hot face (T_c), in a thermoelectric generator, heat conduction, Joule effect and power generation by the Seebeck effect are considered, as shown in equation 27 [III]:

$$\mathrm{Q_{ent}} = ST_cI - \frac{1}{2}RI^2 + \frac{KA(T_c - T_f)}{e} \quad (27)$$

Similarly, the output heat flux (Q_sal) is calculated, considering the above-mentioned effects applied to the wall with the lowest temperature. (T_f).

$$\mathrm{Q_{sal}} = ST_\mathrm{f}I + \frac{1}{2}RI^2 + \frac{KA(T_c - T_f)}{e} \quad (28)$$

To determine the electrical power generated by the thermoelectric plant from the heat input and the heat output, an energy balance is used, which is expressed in the following equation.

$$\mathrm{P_e} = \mathrm{Q_{ent}} - \mathrm{Q_{sal}} \quad (23)$$

4. Results

The results obtained are divided into subsections which are made up of the graphs of Seebeck coefficient, electrical resistivity and thermal conductivity of each one of the thermoelectrics, then with the values obtained the corresponding merit graph will be made, the input and output heat will be calculated to later determine the electrical power generated, finally a comparative table of the power generated by the thermoelectrics and their possible applications is shown.

4.1. ZT Figure of Merit

The figure of merit allows to identify the efficiency of the selected thermoelectric plants, as shown in the following graph 1.

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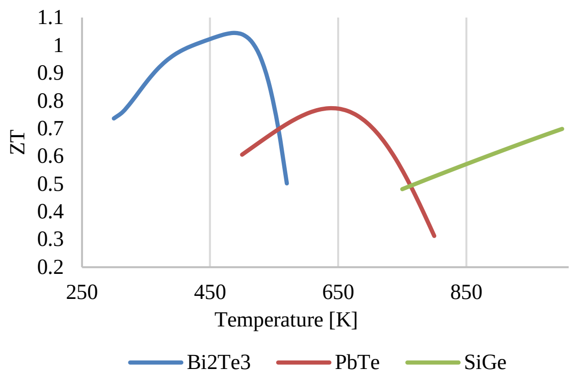
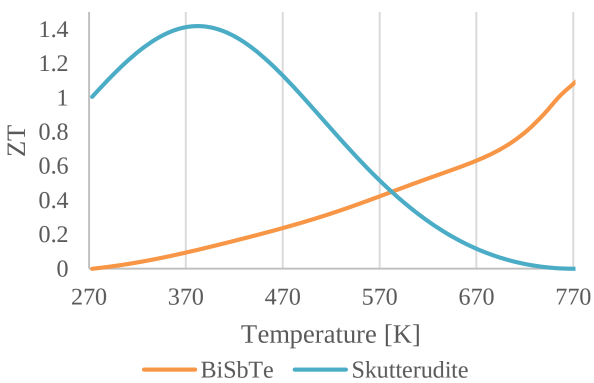


Graph 1 Figure of merit of thermoelectric plants

For the Skutterudite and BiSbTe thermoelectric plants, the following ZT figures of merit are shown in the graph below 2.

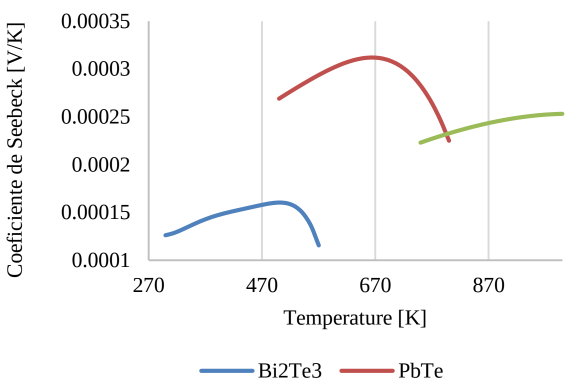


Graph 2 Figure of merit of thermoelectric plants

The selected thermoelectrics have different efficiencies depending on their temperature range, so the higher the ZT, the higher the efficiency.

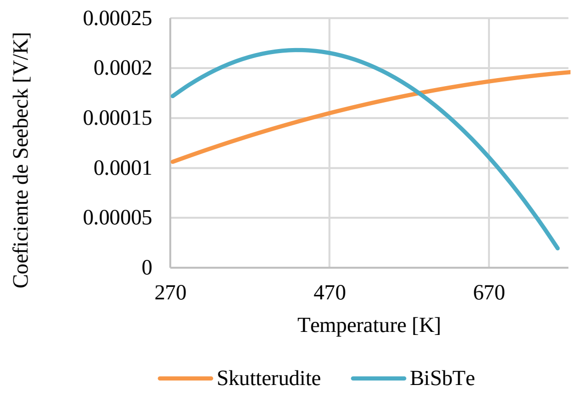
4.2 Seebeck coefficient

The polynomials obtained from the literature are used to calculate the Seebeck coefficient with the corresponding temperatures, which can be represented in the following graphs.



Graph 3 Seebeck Coefficient vs. Bi_2Te_3

For the Seebeck coefficients of the Skutterudite and BiSbTe thermoelectric plants, they have the following ZT figures of merit shown in the chart 2.

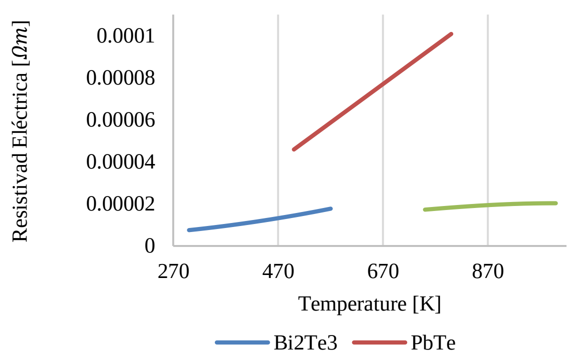


Graph 4 Seebeck Coefficient vs. $PbTe$.

SiGe has the widest temperature range, its coefficient remains relatively high unlike the other thermoelectrics its highest coefficient is at the highest temperature and as the temperature decreases the coefficient decreases.

4.3 Electrical Resistivity

Electrical resistivity refers to a specific point in the material. So what we seek to define is the current density in the resistive material caused. Resistivity, also known as specific resistance of a material is measured in ohms per meter (Ωm). This property changes with respect to the temperature and therefore is different for each thermoelectric, with the polynomials we proceed to make the corresponding graphs shown below.



Graph 5 Seebeck Coefficient vs. $PbTe$.

This graph shows that PbTe has a higher electrical resistivity than Bi_2 Te_3 and SiGe. The following graph shows the electrical resistivity of Skutterudite and BiSbTe.

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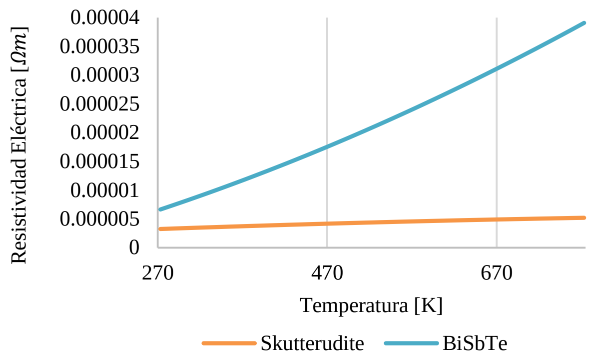


Graph 6 Seebeck Coefficient vs. $PbTe$

It can be observed that unlike the other thermoelectrics analyzed, they have a lower electrical resistivity.

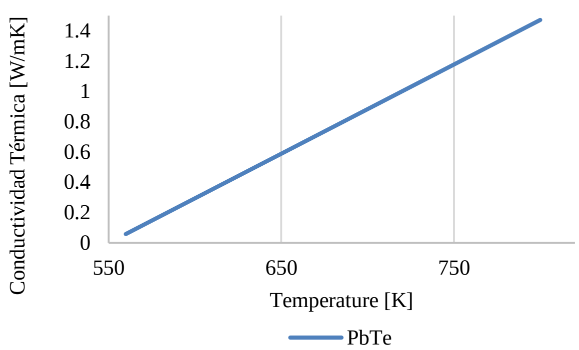
4.4. Thermal Conductivity

Thermal conductivity is important for electrical power calculations, so its polynomials are found as a function of their temperature ranges for some thermoelectrics their thermal conductivity remains constant which are shown in the following table.

Thermal Conductivity	
Thermoelectric	Thermal Conductivity
Bismuth Telluride	$0.85\frac{W}{mK}$
Silicon Germanium	$4.5\frac{W}{mK}$

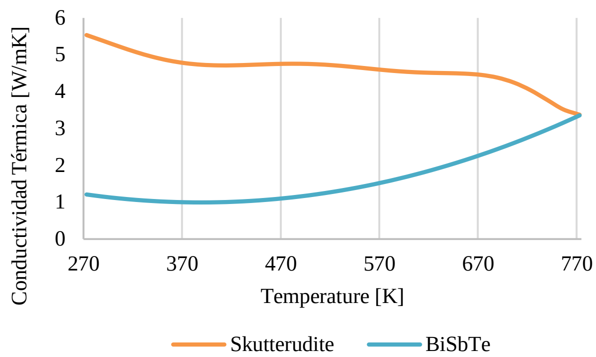
Table 2 Temperature Range Thermoelectrics

For PbTe, Skutterudite and BiSbTe thermoelectrics, the following plots for thermal conductivity are obtained according to their temperature range.



Graph 7 Temperature Range Thermoelectrics

The conductivity varies from 0.05 to 1.47 (W/mK) for PbTe, for the following thermoelectrics are shown in the graph below.



Graph 8 Seebeck Coefficient vs. $PbTe$

It is observed that the Skutterudite thermoelectric has the highest conductivity compared to all the thermoelectrics, with a minimum of 3.37 W/mK and a maximum of 5.53 W/mK.

4.5. Electrical Power

To determine the electrical power is required from the input heat output, it is important to determine the voltage produced, resistance and electrical current. According to Eq.22 the voltage is required a temperature gradient for the hot side in is the operating temperature range, the cold side is influenced by the hot side and by the cooling and radiation systems so it is proposed a temperature for the cold side of the thermoelectric, which is shown in the following table.

Cold Face Temperature	
Thermoelectric	Temperature
Bismuth Telluride	293 K
Lead Telluride	373 K
Silicon Germanium	523 K
Skutterudite	293 K
Bismuth Telluride Antimony	373 K

Table 3 Temperature Range Thermoelectrics

With the temperatures of the cold face, the temperature gradient is substituted in the corresponding equations and the electrical power generated is determined, which is expressed in the following graphs.

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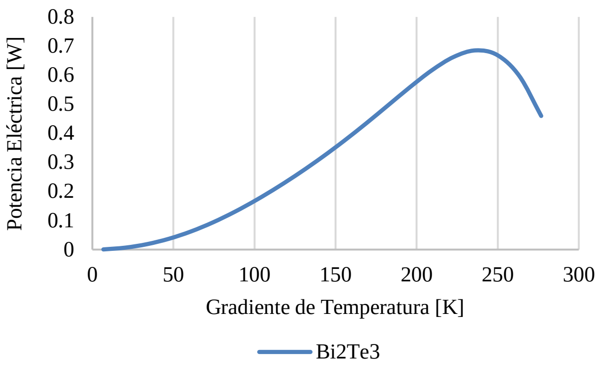
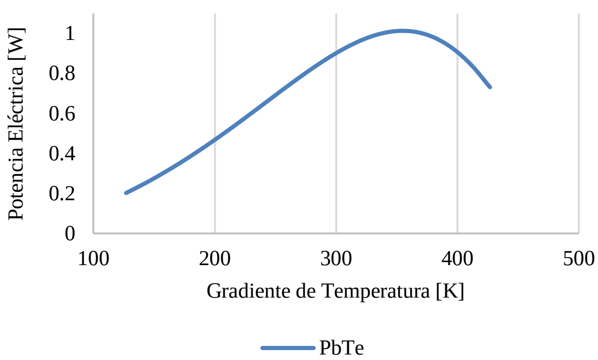
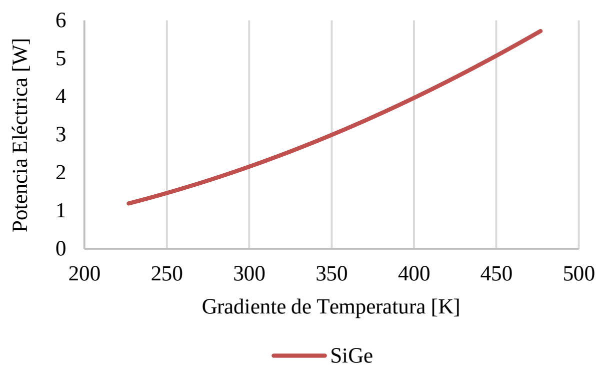


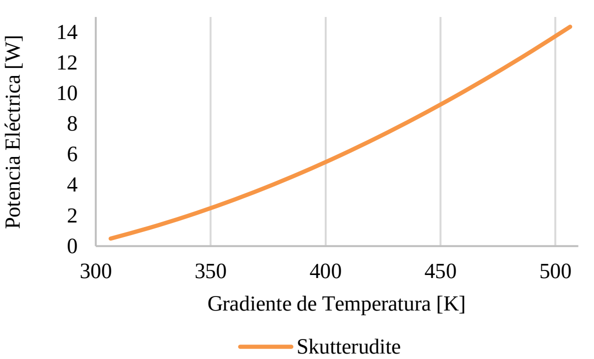
Graph 9 Temperature Range Thermoelectrics



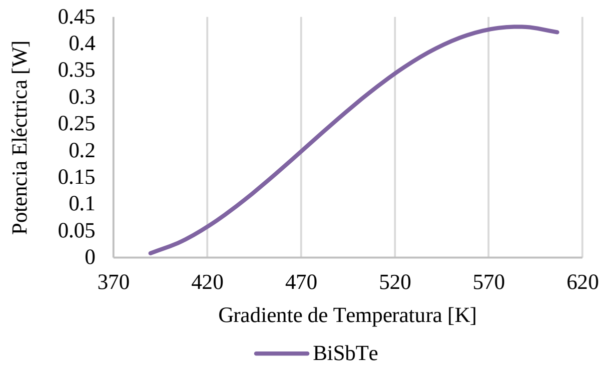
Graph 10 Temperature Range Thermoelectrics



Graph 11 Temperature Range Thermoelectrics



Graph 12 Temperature Range Thermoelectrics.



Graph 13 Temperature Range Thermoelectrics

Below is a table with the maximum and minimum values obtained for the electrical power generated with their respective temperature gradient ranges..

Electrical Power Generated [W] [W		
Thermoelectric	Max	Min
Skutterudite	14.4	0.49
$SiGe$	5.7	1.18
$PbTe$	1.0	0.2
Bi_2Te_3	0.68	0.0007
$BiSbTe$	0.43	0.008

It can be seen that the thermoelectric with the highest conversion range is the Skutterudite, so it follows the behavior of the ZT figure of merit as expected, followed by the German Silicon thermoelectric and so on until the end with the BiSbTe which presents the lowest electrical power that has been calculated.

Application	
Thermoelectric	Application
Skutterudite	Low Thermal Power Piping
$SiGe$	Radioisotope Generators and Nuclear Rectors
$PbTe$	Radioisotope Generators
Bi_2Te_3	Radioisotope Generators and Low Power Pipelines
$BiSbTe$	Low Thermal Power Piping

Although Skutterudite has higher efficiency than other thermoelectrics, it is limited by the low operating range, so proper considerations must be made for the implementation of each of the thermoelectrics shown in the paper.

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5. Conclusions

It can be seen that the thermoelectric with the highest conversion efficiency is the Skutterudite with a maximum conversion of 14.4W, however its operating temperature range is low so it can only work for systems where the input temperature is low, on the other hand the Germanium Silicon presents a maximum electrical power of 5.7W which shows that although its conversion is low it can work at high temperatures allowing to have a greater flexibility for systems such as radioisotope generators or nuclear reactors for space exploration. On the other hand, it is necessary to take into consideration the phenomena of convection and radiation for the cold side. In conclusion, it is clear that thermoelectrics have a low efficiency, but they can be used in the aerospace sector since they do not have moving or mechanical parts and do not require maintenance, thus allowing their application in various systems where the electrical energy generated by these themselves is not the main source of generation, but works in conjunction with other power conversion systems.

6. Funding

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7. References

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