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Analysis of the electrical power generated by a thermoelectric system for application in the Ingenuity drone from a nuclear heat source

Análisis de la potencia eléctrica generada por un sistema termoeléctrico para su aplicación en el Dron Ingenuity a partir de una fuente de calor nuclear

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Abstract

The aerospace sector has made great strides in the development of electrical power generation in space exploration missions. The ingenity drone is a technological demonstration of flight on the planet Mars, using a solar panel as a source of electrical power generation, however, obtaining power is limited to the atmospheric conditions of Mars and climatic changes such as sandstorms. Thermoelectrics are a good option for power generation in the ingenuity drone since they do not require sunlight to generate electricity, thermoelectrics require a temperature differential to generate a voltage differential this physical phenomenon is known as the seebeck effect. The use of thermoelectrics is exploited by a source of nuclear heat that can reach high temperatures due to the disintegration of radioactive isotopes, so it is necessary that thermoelectrics have a high temperature range. Some thermoelectricals proposed for this work are Bi_2 Te_3, PbTe and SiGe according to their operating characteristics at high temperatures, can be exploited by a source of nuclear heat for the generation of electricity. For this the electrical power required for an axial or stationary flight is calculated, so it is necessary to know some characteristics of the ingenuity drone, as well as the atmospheric conditions of the planet Mars. According to the temperature range of the selected thermoelectrics are determined some properties such as the seececk coefficient, thermal conductivity and electrical resistivity, with these properties is calculated the electrical power required for axial flight and the amount required. According to the electrical power of each thermoelectric is calculated the thermal power required for operation of a source of nuclear heat in its application in the drone.

Drone ingenuity, Thermoelectric, Nuclear heat source

Resumen

El sector aeroespacial ha tenido un gran avance en el desarrollo de generación de energía eléctrica en misiones de exploración espacial. El Dron Ingenity es una demostración tecnológica de vuelo en el planeta Marte, utiliza un panel solar como fuente de generación de energía eléctrica, sin embargo, la obtención de energía se ve limitado a las condiciones atmosféricas de Marte y los cambios climáticos, como tormentas de arena. Los termoeléctricos son una buena opción para la generación de energía en el Dron Ingenuity ya que no requieren de la luz solar para generar energía eléctrica, los termoeléctricos requieren de un diferencial de temperatura para genera un diferencial de voltaje a este fenómeno físico se le conoce como efecto Seebeck. El uso de los termoeléctricos es aprovechado por una fuente de calor nuclear que puede alcanzar altas temperaturas producto de la desintegración de isotopos radiactivos, por lo que es necesario que los termoeléctricos tengan un alto rango de temperatura. Algunos termoeléctricos propuestos para este trabajo son Bi_2 Te_3, PbTe y SiGe de acuerdo con sus características de operación a altas temperaturas, pueden ser aprovechados por una fuente de calor nuclear para la generación de energía eléctrica. Para esto, se calcula la potencia eléctrica requerida para un vuelo axial o estacionario, por lo que es necesario conocer algunas características del Dron Ingenuity, así como condiciones atmosféricas del planeta Marte. De acuerdo con el rango de temperatura de los termoeléctricos seleccionados se determinan algunas propiedades como el coeficiente de Seececk, conductividad térmica y resistividad eléctrica, con estas propiedades se calcula la potencia eléctrica de los termoeléctricos y la cantidad requerida para el vuelo axial. De acuerdo con las potencias eléctricas de cada termoeléctrico se calcula la potencia térmica necesaria de operación para una fuente de calor nuclear en su aplicación para el Dron.

Dron Ingenuity, Termoeléctrico, Fuente de Calor Nuclear

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Introduction

The development of electric power generation in the aerospace sector is one of the most important developing topics due to its technological contribution, where the supply of electric power is sought in missions that require long distance travel, such as satellites, space stations, space probes, rovers and recently drones. The Ingenuity Drone mission is a technological demonstration that aims to test the flight in the atmosphere of Mars, thus becoming the first unmanned aircraft outside the planet Earth. The way of obtaining energy is from a solar panel, placed on top of the propellers, which uses the light it receives during the day, and may vary depending on the seasons and weather changes on Mars such as dust storms that may prevent the operation of the solar panel, so it is important to propose other ways of obtaining energy. Thermoelectric materials are used for the generation of electrical energy through a temperature differential, this physical phenomenon is known as Seebeck effect, thermoelectrics could be a good option for the application in the Ingenuity Drone and in future drone missions, since they do not depend on climate changes, as well as the distance from the sun. The use of thermoelectrics in space missions has its application in the Multimission Radioisotope Thermoelectric Generator (MMRTG), which harnesses the heat generated by radioactive decay from the General Purpose Heat Source (GPHS). The nuclear heat source can reach high temperatures due to decay, so the thermoelectrics selected for this work must have a high operating range. The selected thermoelectrics that meet these characteristics are Bi_2Te_3, $PbTe$ and SiG, making them viable candidates for implementation in the Ingenuity Drone.

The analysis of the electrical power generated by the thermoelectrics, as well as the amount of thermoelectrics needed for the implementation in the Ingenuity Drone could be a starting point in future drone missions, for that reason the Ingenuity Drone is considered for this work since it is the only drone that exists outside the planet Earth. To obtain the electrical power, the drone is analyzed in an axial or stationary flight, so it is important to know some of the characteristics of the Ingenuity Drone, such as the mass of the drone and the diameter of the rotors, as well as the flight conditions in the atmosphere of the planet Mars, such as density and gravity. According to the thermoelectrics proposed for this work, some properties such as the Seebeck coefficient, electrical resistivity and thermal conductivity are obtained. From these properties, the electrical power generated by the thermoelectrics is calculated and the amount needed to generate the axial flight electrical power for the Ingenuity Drone is estimated. With the electrical power generated by the thermoelectrics, the necessary thermal power at which the nuclear heat source must operate is calculated.

Methodology

The present work has the following methodology to be developed:

Review the flight characteristics in the conditions of the planet Mars and the main operating characteristics of the Ingenuity Drone.

- Calculate the mechanical power of the rotors and obtain the electrical energy consumed by the Drone.

- Propose the types of thermoelectrics to convert the thermal power of the nuclear heat source into electricity.

- Calculate the Seebeck coefficient, electrical resistivity and thermal conductivity as a function of the temperature ranges of the thermoelectrics.

- Calculate the electrical power generated by each type of thermoelectric.

- Obtain the thermal power of the nuclear heat source for each of the thermoelectric types.

Development

Flight conditions on the planet Mars

The possibilities of flight on Mars are dominated by the low density of the Martian atmosphere. The density on Mars is approximately 1% of Earth's, which varies between 0.010 and 0.020 $\frac{kg}{m^3}$ depending on altitude and time of year [I]. The flight dynamics of the Ingenuity Drone are significantly affected due to the low atmospheric density and low gravity (38% of Earth's gravity). In addition, the atmospheric conditions on Mars are colder reaching up to -50°C, resulting in different aerodynamic conditions of in the propellers [II]. Table 1 shows some characteristics of the planet Mars.

Planet Mars conditions	
Density	0.017 kg/m^3
Gravity	3.711 m/s^2
Temperature	-50 °C

Table 1 Flight conditions on the planet Mars

Main operating characteristics of the Ingenuity Drone

The Ingenuity drone has a mass of 1.8 kg in vacuum, which is made up of all mechanical, electrical and electronic components. The drone's battery consists of 6 lithium-ion cells with a nominal capacity of 2 Ah at 4.25V [II]. The rotor system provides the lift for the drone, as well as the forces necessary for directional control of its trajectory. The design uses two coaxial counter-rotating rotors of 1.21 m diameter each. The traction to be generated by the drone is equal to its own weight, so each rotor has to provide a traction of 0.9 kg (3.33 N). Each rotor requires an electrical power to achieve lift on Mars, for this it is important to consider the characteristics shown in Table 2.

Ingenuity Drone features	
Drone Mass	1.8 Kg
Rotor diameter	1.21 m
Batteries mass	273 g
Battery capacity	2Ah a 4.25V

Table 2 Main characteristics of the Igenuity Drone

Calculation of power required for the drone

For the sizing of the amount of electrical power generated by the thermoelectrics for the Ingenuity Drone, the required power is first determined, which is sufficient to meet an axial flight, in a floating state, for which the Rankine and Froude theory is used.

The general equation of mass flow, momentum and conservation of energy can be applied to a floating rotor. Figure 1 represents the drone rotor in an axial ascent with velocity V_c, for which the hovering condition is obtained at the boundary $V_c \rightarrow 0$, this corresponds to the condition $V_c=0$ as shown in Figure 1. The cross section is 0 in the rotor plane, where in the hovering case the fluid is inactive (i.e., $V_0 = V_c = 0$). Cross sections 1 and 2 are the planes just above and below the rotor, respectively, and the wake (the wake below the rotor) is denoted by the cross section ∞. In the rotor plane, the velocity (the induced velocity or the velocity imparted to the air mass contained in the control volume in the rotor disk) is assumed to be v_i, In the far wake (the current slip), the velocity will increase above that in the rotor plane, and this velocity is denoted by W. The area of the rotor disk is denoted by A. From the assumption that the flow is nearly constant and by the principle of conservation of mass, the mass flow rate $\dot{m}$ must be constant within the limits of the rotor wake control volume.

The actuating disk supports the thrust force generated by the rotation of the rotor blades around the shaft and its action on the CO_2. To generate this thrust, power is required, which is supplied in the form of torque to the thrust shaft. The work done on the rotor leads to a gain of kinetic energy of the rotor wake and this is an energy loss which is called induced power.

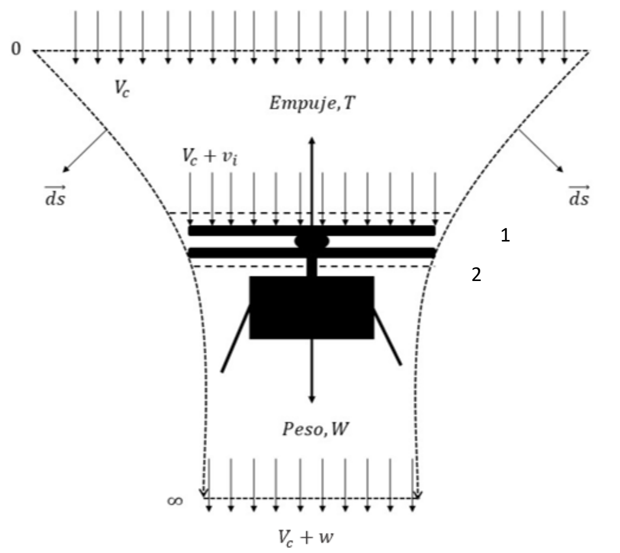

Figure 1 Analysis of the thrust theory of a rotor in axial flight

Stationary flight is a unique flight condition. Here the rotor has zero vertical velocity. The rotor flow field is therefore axisymmetric. In the general approach to the problem, the flow through the rotor will be assumed to be one-dimensional. The momentum theory approach allows to derive a prediction of the thrust and power of the engine. For the calculation of the rotor power it is necessary to know the thrust T generated by the drone which is calculated as follows:

$$\mathrm{T} = m * g \tag{1}$$

Where:

T = Thrust $[N]$..

m = Mass of Ingenuity Drone $[Kg]$.

g = Gravity on Mars $\left[\frac{m}{s^2}\right]$.

According to Newton's third law or action-reaction principle, the weight (W) of the Drone has to equal thrust (T) in order to have an axial flight. Momentum theory can be used to relate the thrust of the rotor using the equation:

$$\mathrm{T} = 2 * \rho * \mathrm{A} * v_i^2 \tag{2}$$

Where:

T = Thrust$[N]$.
ρ = Density on Mars $\left[\frac{kg}{m^3}\right]$.
A = Drone Rotor Area $[m^3]$.
v_i = Induction speed $\left[\frac{m}{s}\right]$.

In the plane of the rotor, the velocity is the induced velocity (vi) or air mass velocity contained in the rotor disk, so it can be obtained that the induced velocity in stationary flight is:

$$v_i = \sqrt{\frac{T}{2*\rho*\mathrm{A}}} \tag{3}$$

Substituting Eq.1 in Eq.3.

$$v_i = \sqrt{\frac{m*g}{2*\rho*\mathrm{A}}} \tag{4}$$

The theory of quantity of motion allows the prediction of rotor thrust and power. For in this way the power is the multiplication of the induced speed and the thrust which generates the following equation.

$$P = 2 * \rho * \mathrm{A} * v_i^3 \tag{6}$$

The calculated power is for each of the rotors so it is important to note that the Ingenuity Drone has two rotors that allow axial flight, also the power can be considered as the energy that is transferred to the rotor.

Analysis of selected thermoelectrics.

Thermoelectrics are capable of converting thermal energy into electrical energy, this effect is known as Seebeck. When two different semiconductors are connected to each other, the temperature difference between them causes a potential difference at the point of contact, which generates an electric current in the conductors that form the circuit. For space exploration, the use of thermoelectrics favors the generation of electrical energy without the need to use solar panels. Once the power required by the Ingenuity Drone rotors for an axial flight has been calculated, it is important to know the types of thermoelectrics and their quantity to supply the power required by the drone. Thermoelectrics work under a range of temperatures that can change according to the materials to be used. The dimensions of the thermoelectrics are 8mm long, 10mm wide and 2.5mm thick [III]. The materials selected for the thermoelectric system are:

- Bismuth Telluride (Bi_2Te_3).
- Lead Telluride ($PbTe$).
- Silicon Germanium ($SiGe$)

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They are selected for having a high operating temperature range, so the figure of merit denoted as ZT is used to determine the efficiency of thermoelectrics. The ZT value is a dimensionless index. It increases with the square of the Seebeck coefficient, with the average absolute operating temperature and electrical conductivity. It decreases with the specific thermal conductivity. This can be represented in equation (7).

$$\mathrm{ZT} = \frac{S^2 * \sigma}{k} * T \quad (7)$$

Where:

ZT = Figure of merit.

S = Seebeck coefficient $\left[\frac{V}{K}\right]$.

σ = Electrical Conductivity$\left[\frac{1}{\Omega * m}\right]$.

k = Thermal conductivity$\left[\frac{W}{m * K}\right]$.

T = Absolute temperature$[K]$.

Calculation of thermoelectric power

To calculate the electrical power generated it is necessary to know the thermoelectric properties which are:

- Seebeck coefficient (S, $\left[\frac{V}{K}\right]$).
- Electrical Resistivity (ρ, $[\Omega * m]$).
- Electrical Conductivity (k, $\left[\frac{W}{m * K}\right]$).
- 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_2Te_3 is found as a function of the temperature range from 300K to 570K, which is expressed in Eq.8 and Eq.9.

$$S(z) = -1.9 * 10^{-6}z^5 - 0.12 * 10^{-6}z^4 + 4.1 * 10^{-6}z^3 - 3.4 * 10^{-6}z^2 + 11 * 10^{-6}z + 1.5 * 10^{-6} \quad (8)$$

$$\rho(z) = 2.5 * 10^{-7}z^2 + 2.7 * 10^{-6}z + 4.1 * 10^{-5} \quad (9)$$

Where the value of z is expressed in Eq.10.

$$z = \frac{T - 4.1 * 10^2}{76} \quad (10)$$

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

$$S(z_s) = -8.2 * 10^{-6}z_s^4 - 7.3 * 10^{-6}z_s^3 - 7.9 * 10^{-6}z_s^2 + 54 * 10^{-6}z_s + 2.8 * 10^{-4} \quad (11)$$

$$\rho(z_r) = 6.4 * 10^{-5}z_r + 5.5 * 10^{-5} \quad (12)$$

$$k(z_k) = 0.23 * z_k^2 - 0.28 * z_k + 1.2 \quad (13)$$

Where the values of z_s, z_r *and* z_k are expressed in the following equations:

$$z_s = \frac{T - 5.3 * 10^2}{150} \quad (14)$$

$$z_r = \frac{T - 5.3 * 10^2}{350} \quad (15)$$

$$z_k = \frac{T - 5.3 * 10^2}{170} \quad (16)$$

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

$$S(z_s) = -4.5 * 10^{-6}z_s^3 - 9.6 * 10^{-6}z_s^2 + 6 * 10^{-5}z_s + 0.0002 \quad (17)$$

$$\rho(z_r) = 1/(8.7 * 10^3 z_r^2 - 2.5 * 10^4 z_r + 6.7 * 10^4) \quad (18)$$

Where the values for z_s and z_r are expressed in the following equations:

$$z_s = \frac{T - 6.5 * 10^2}{240} \quad (19)$$

$$z_r = \frac{T - 6.5 * 10^2}{240} \quad (20)$$

The thermal conductivity of $SiGe$in the temperature range used is practically constant, $4.5 \frac{W}{m*K}$[III]. With the Seebeck coefficient (S) of each of the thermoelectrics, the voltage produced according to the temperature range of each thermoelectric and the ambient temperature of Mars, the voltage produced by the semiconductors is obtained according to the principle of the Seebeck effect shown in Equation 21:

$$V = S * (T_c - T_f) \quad (21)$$

Where:

V = Voltage $[V]$.

S = Seebeck Coefficient $\left[\frac{V}{K}\right]$.

T_c = Temperature on the hot face $[K]$.

T_f = Cold face temperatura $[K]$.

The electrical resistance of the thermoelectric is determined with Equation 22.

$$R = \rho \frac{e}{A} \quad (22)$$

Where:

ρ = Electrical Resistivity $[\Omega * m]$.

e = Thermoelectric thickness $[m]$.

A = Thermoelectric Area $[m^2]$.

The electrical power generated is calculated using Equation 23.

$$P = S * I * (T_c - T_f) - R * I^2 \quad (23)$$

To obtain the peak current, the electrical power is partially derived with respect to the current and equals zero as shown in Equation 24.

$$\frac{\partial P}{\partial I} = 0 = S(T_c - T_f) - 2RI \quad (24)$$

With the voltage and resistance calculated according to the temperature range of each of the thermoelectrics, the maximum electric current is calculated using Equation 25.

$$I_{max} = \frac{V}{2R} \quad (25)$$

The calculation of the electrical power generated by the thermoelectrics according to their respective temperature ranges, allows to know the amount required for an axial flight and according to the conditions of Mars.

Thermal power required for nuclear heat source

The general purpose heat source (GPHS) is a nuclear source used mainly in space missions, inside it contains a radioactive isotope that serves as nuclear fuel, the heat generated from radioactive decay is used by thermoelectrics to generate electricity, so it is important to know the thermal input and output power of thermoelectrics for the design of a nuclear heat source. To determine the heat input (Q_{in}), at the hot face (T_c), in a thermoelectric generator, heat conduction, Joule effect and power generation by Seebeck effect are considered, as shown in equation 25 [III]:

$$Q_{in} = S * T_c * I - \frac{1}{2} * R * I^2 + \frac{K*(T_c - T_f)}{e} \quad (26)$$

Similarly, the outgoing heat flux (Q_{out}) is calculated, considering the above mentioned effects applied to the wall with the lowest temperature (T_f).

$$Q_{out} = S * T_f * I - \frac{1}{2} * R * I^2 + \frac{K*(T_c - T_f)}{e} \quad (27)$$

This provides the heat range for the design of a nuclear heat source for the Ingenuity drone application for this work.

Results

The obtained results are divided into the subsections of power required for an axial flight, merit graph of the thermoelectrics, Seebeck coefficient for the temperature range, power of the thermoelectrics according to the temperature range, amount of thermoelectrics needed for the Ingenuity Drone and range of thermal power according to the thermoelectrics needed for the nuclear heat source.

Power required for an axial flight

Table 3 shows the results obtained for an axial flight according to the characteristics of the Ingenuity Drone and the conditions of the planet Mars.

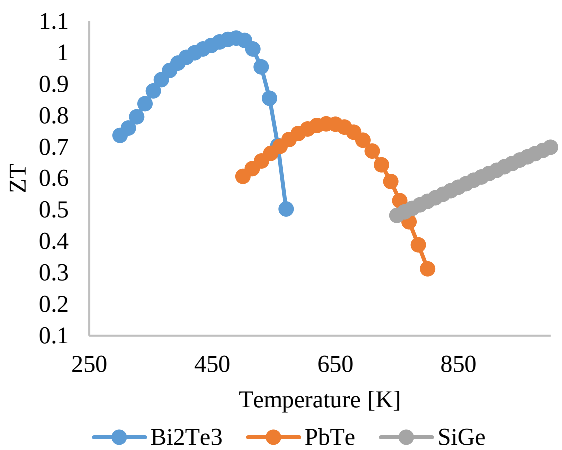
Axial flight results	
Rotor drive	0.9 kg
Rotor disc area	1.1499 m
Induction speed	9.2426 $\frac{m}{s}$
Mass flow	0.1806 $\frac{kg}{s}$
Power per Rotor	30.869 W
Total power in axial flight	61.74 W
Take-off power	370.44W

Table 3 Axial flight results for the Ingenuity Drone.

As can be seen, the power of each rotor is added to get the total power required for axial flight. With the calculated power, the analysis of the thermoelectrics required for the flight is performed.

Graph of merit

The graphic of merit allows identifying the efficiency of the selected thermoelectric plants, as shown in graphic 1.

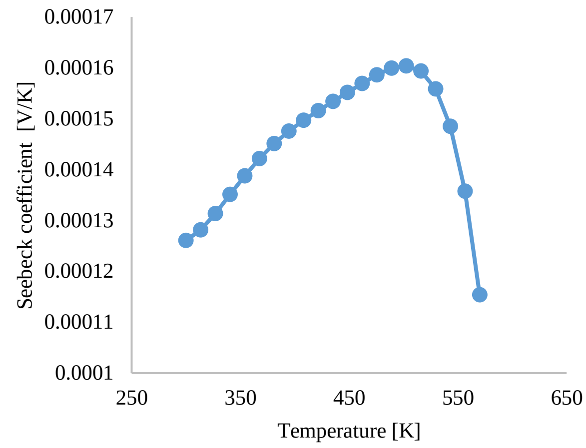


Graphic 1 Figure of merit of thermoelectric plants

The selected thermoelectrics have different efficiencies depending on their temperature range, so the higher the ZT, the higher the efficiency of thermal to electrical energy conversion. It can be observed that the Bi_2Te_3 has the highest efficiency range, but it is also the one with the lowest temperature range of the 3 selected thermoelectrics.

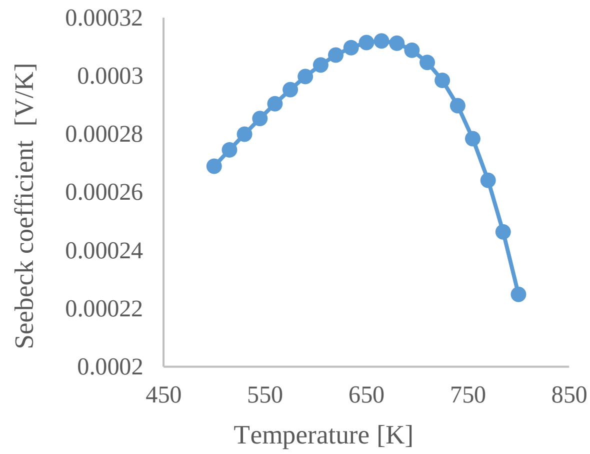
4.3 Seebeck coefficient

With the polynomials obtained from the bibliography, the Seebeck coefficient is calculated with the corresponding temperatures, which can be represented in the following graphs.



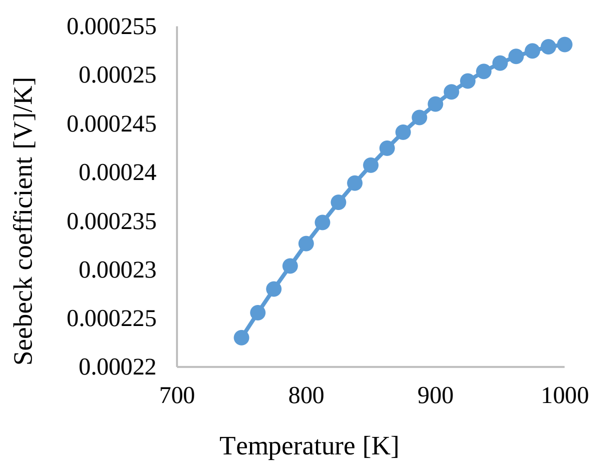
Graphic 2 Seebeck coefficient vs. temperature of Bi_2Te_3

The Bi_2Te_3 despite having a high merit number has the lowest temperature range and a low Seebeck coefficient, but it can be observed that its highest coefficient point is near the middle of its temperature range.



Graphic 3 Seebeck coefficient vs. temperature of $PbTe$

$PbTe$ has the highest Seebeck coefficient, and like the previous material, its highest coefficient is in the central zone of the temperature range.

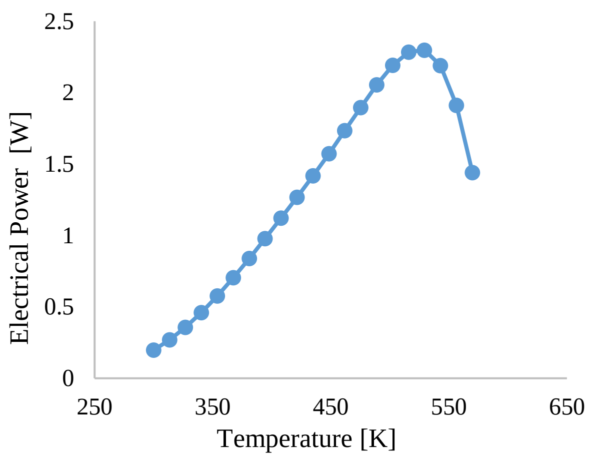


Graphic 4 Seebeck Coefficient vs. Temperature of $SiGe$

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

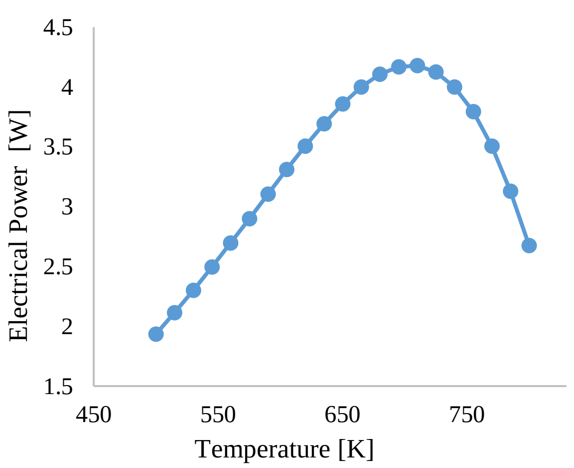
Electrical power of the thermoelectrics

With the values of the Seebeck coefficient, voltage, electrical resistance, electrical current and electrical conductivity of each of the thermoelectrics, the electrical power generated by the thermoelectrics was calculated by taking the ambient temperature of Mars which is -50°C to generate the temperature differential, which can be represented in the following graphs.



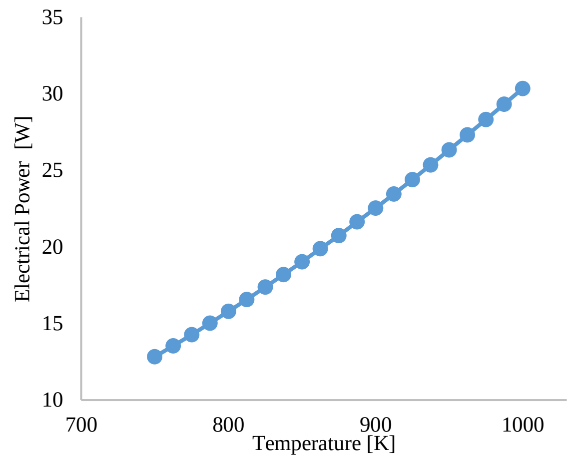
Graphic 5 Electrical Power vs Temperature of Bi_2Te_3

The temperature on the cold side of the thermoelectric is maintained at Mars ambient temperature while the hot side is in the operating range of the thermoelectric. For $Bi_2Te_3$the maximum electrical power is reached at 500K, so it is a relatively low power.



Graphic 6 Electrical Power vs Temperature of $PbTe$

The thermoelectric PbTe has a higher electrical power Bi_2Te_3, the highest electrical power it reaches is around 700K. It is a higher power at a suitable temperature for the implementation in the drone.

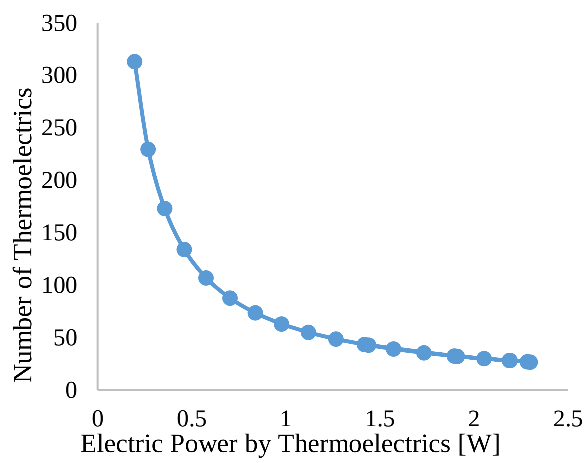


Graphic 7 Electrical Power vs. Temperature of $SiGe$.

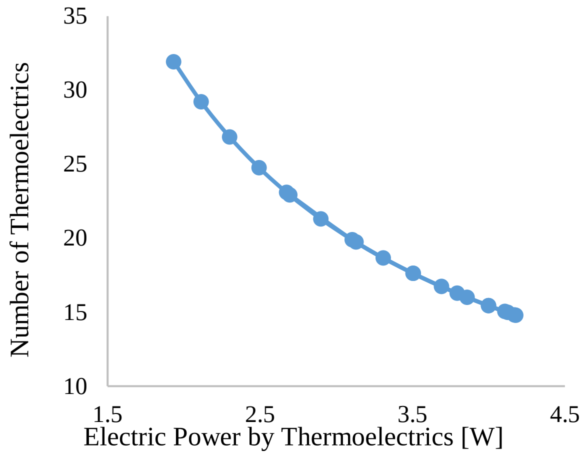
The electrical power of $SiGe$.is by far the highest of the selected thermoelectrics. It reaches its electrical power at the highest operating temperature and decays as the temperature on the hot face decays.

Number of thermoelectrics

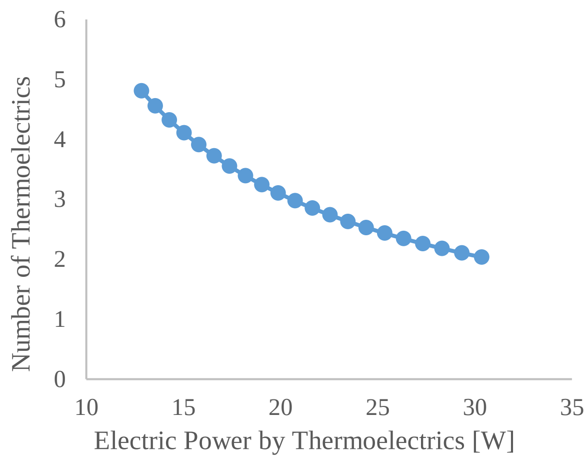
Having knowledge of the electrical power generated by the thermoelectrics we estimate the amount needed to generate the flight power for the Ingenuity Drone.



Graphic 8 Quantity of Thermoelectrics vs Electrical Power of Bi_2Te_3



Graphic 9 Quantity of Thermoelectrics vs Electric Power of $PbTe$

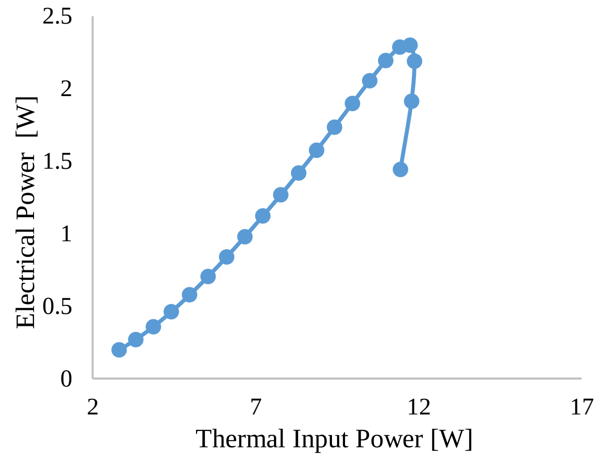


Graphic 10 Quantity of Thermoelectrics vs Electrical Power $SiGe$

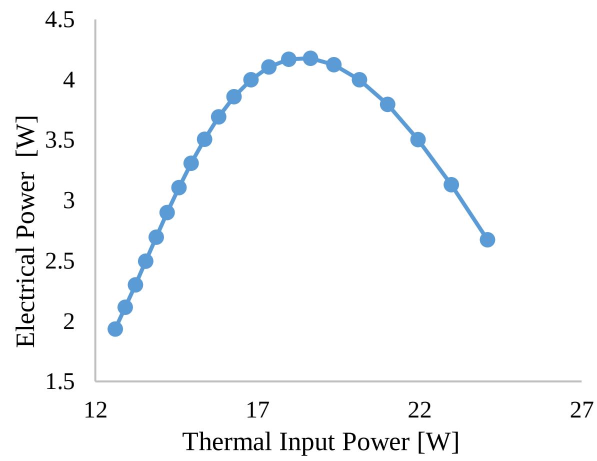
$SiGe$ requires the least amount of thermoelectrics compared to Bi_2Te_3 and $PbTe$, the latter requiring more thermoelectrics to generate the electrical power for axial flight. Despite having a relatively low figure of merit SiGe and having a high temperature range is able to generate more electrical power.

Thermal power for the nuclear heat source

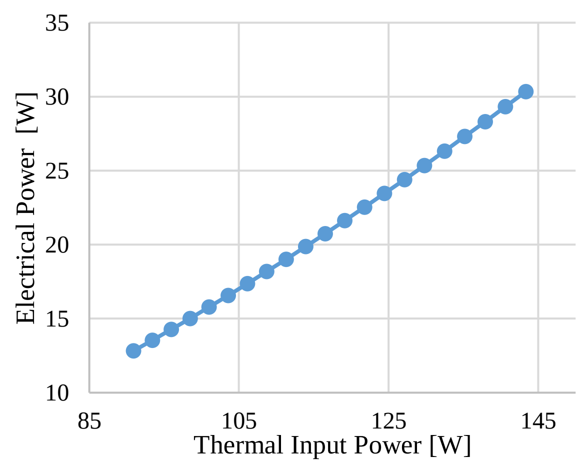
Thermoelectrics in space missions convert the thermal energy generated by nuclear heat sources into electrical energy. In the following results the thermal power at the input of the thermoelectric is shown as this way the thermal power of operation of the nuclear heat source is estimated.



Graphic 11 Electrical Power vs Thermal Power at the input of Bi_2Te_3



Graphic 12 Electrical Power vs Thermal Power at the $PbTe$ input



Graphic 13 Electrical Power vs. Thermal Power at $SiGe$ input

It can be seen that thermoelectrics can work at different thermal input powers, unfortunately not all the thermal power is utilized so only a small fraction is converted, nuclear heat sources leave to operate in high temperature ranges so the $SiGe$ thermoelectric is the best candidate for implementation in the Ingenuity Drone.

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Conclusion

The analysis of the power generated by the thermoelectric systems in the implementation of the Ingenuity Drone, can change according to the thermoelectric to be used. The Bi_2Te_3 requires a large amount to produce the required power, despite having a high number in the graph of merit could not be possible its implementation the drone, while $PbTe$ requires a moderate amount but still remains high, the $SiGe$ does not require large amounts compared to the other thermoelectrics. In conclusion, for implementation in the Ingenuity Drone, he $SiGe$ is the best candidate to supply the required electrical power in its flight, with the least amount of thermoelectrics, also it is the best candidate for a nuclear heat source as they usually work at high temperatures.

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