Study of nuclear energy as an alternative energy source in satellites applying the SPDC effect

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ABSTRACT :
The objective of this study is to look for an alternative in the collection of energy in satellites without the inefficient conversion of solar energy and, since in the area of umbra or eclipse, when it does not receive direct solar radiation, problems may arise because it does not have enough energy supply to function, so, nuclear energy is considered as an alternative energy source applying the SPDC effect (spontaneous parametric descending conversion), waiting for the satellite to supply energy anywhere it is located. Similarly, it was determined that by using nuclear material as an energy source, it not only improves but also optimizes energy supply in space missions with CubeSat nanosatellites. Based on the results of the study, it is concluded that not only would the supply of satellites be optimized, but also would lead to savings in the cost of producing them.

KEYWORDS: nuclear power, solar power, supply, CubeSat satellites, SPDC effect.

I. INTRODUCTION

Currently, the primary source for the supply of energy in the satellites is the sun, the solar radiation is converted into electricity by means of solar cells, but these do not have great efficiency in the conversion of solar radiation into electrical power, being in charge of feeding all its systems, as well as the communications, commands, control, among others. The energy supplied varies due to the translational motion on Earth [1] and its consumption will vary depending on the type of orbit and the modes of operation [2]. The use of solar panels as solar power transformers in electric present drawbacks at the time of energy collection in the shaded area.

According to the above, advances in satellite technology have improved the power modules of the satellites by means of EPS (Electrical Power Systems) in charge of supplying energy and ensuring that the satellite has enough energy in the sunlight phase to charge the battery and to compensate the loss in the shadow phase [3] in the CubeSat satellites standardized in the nano satellite category whose measures of length, width and length are 10cm x 10cm x 10cm and a total weight of no more than 1.33Kg.

Thus, despite the improvements compared to the supply of energy through EPS are disadvantages due to the operating times when they are in the shade, at which time the sun cannot radiate the satellite, so these must endure extreme temperatures ranging from -40 º C to 85 º C as a result of solar radiation, infrared radiation directly, and by the time of eclipse [2], is how CubeSat satellites must keep all its components isolated and working, acquiring great responsibility in the management of all systems.

Therefore, it is necessary to consider alternative energy supplies in which the satellite can maintain its correct operation. Thus, the possibility of changing the source of solar energy to alternative energies, in this case, to nuclear energy, is considered [4], being this an energy source that guarantees the supply of electrical energy, slows down contaminating emissions, reduces external energy dependence and produces electricity in a constant way with low, stable and predictable prices [5].

This paper addresses the study of nuclear radiation as a means of energy supply of a CubeSat satellite. This type of energy would come from the Gamma decay, which would allow the use of waste material from nuclear plants, taking into account that the main forms of radiation are: i) neutron emission; ii) gamma radiation, that is, electromagnetic radiation, of the same nature as visible light, microwaves or X-rays, but more energetic; iii) alpha radiation; iv) beta radiation, that is how the operation of these satellites in any space mission would allow their electronic components to work efficiently and be permanently supplied without the need to limit themselves to a loading time [6].

The manufacturing techniques have allowed to significantly reduce the size and mass of the satellites, allowing to continue with the good performance and usefulness of the same with a low cost and accessible in different countries, these satellites are ideal for projects of spatial development for colleges and universities around the world [7]. Therefore, several articles show the progress for the improvement of the batteries of satellites CubeSat, focusing on the characterization of battery technologies [8].

Similarly, power modules were developed for the CubeSat UD Colombia 1 experimental satellite peak through the Power Module project, making a printed circuit board and the assembly of the component [2].

Similarly, research on multi-joint solar cell technologies, which presents a prototype photovoltaic panels of the CubeSat Colombia 1 satellite Pico of the Francisco José de Caldas district University using Pspice software [9]. Research was obtained on the possibilities of solar cells and commercial photodiodes as orientation sensors in CubeSat satellites, to determine their behavior with respect to the angle of incidence of sunlight [10].

A. THEORETICAL FRAMEWORK

CubeSat satellites are classified by their standard weight and size, usually weighing less than 10 Kg, divided according to their physical volume CubeSat 1U (10cm) 2U (2 times larger in size) 3U (weight approx. 3Kg) 6U and 12U the energy subsystem is in charge of giving power to the rest of the systems for its operation [11], being captured by means of solar panels [12], according to its size. The size of the solar panels is restricted and therefore, the available energy and its stored reserves, limiting data processing capacity making it difficult to use for computationally intensive missions. Its power budget varies from 2 to 8 watts, defining the combined payload consumption, based on the power production of all components. To date, several prototypes have been launched for different missions being the CubeSat 3U 57% of missions [11].

The orbit of the CubeSat is solar synchronous, that is, it rotates approximately one degree per day to maintain its orientation to the sun. 1) [13].

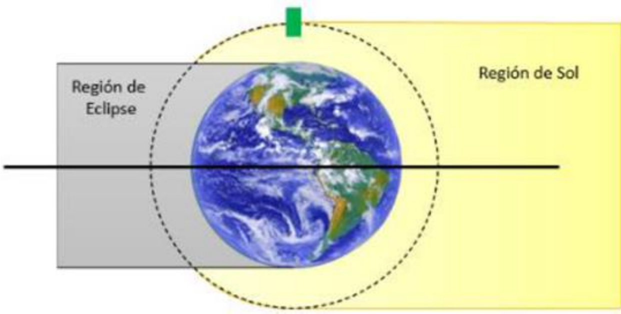


Fig. 1: Movement of a satellite and eclipse or umbra. Adapted from [12].

The electrical energy through the electrical photo effect consists in the use of semiconductor materials, when a material of this type absorbs solar radiation, positive and negative charges are generated in the same that are collected in corresponding electrodes and finally pass to an electrical circuit [14].

B. NUCLEAR ENERGY

It is the energy from nuclear reactions such as fusion, fission and decay, as these are occurring naturally or man-made. Nuclear fusion is a process in which two atomic nuclei form a single one. The reactions produced by fission are due to the rupture of a nucleus splitting into two or more nuclei and the decay of a nucleus is evidenced when there is a process of spontaneous disintegration of the nucleus, and the result in the emission of radiation, releasing enough energy with little nuclear material.

The basic processes of radiation are divided into two categories, 1) radioactivity [15] which is a physical phenomenon characterized by the disintegration of unstable atomic nuclei, according to the atom. The disintegration occurs through emissions such as; a) alpha: the emitted particle corresponds to a nucleus of the chemical element helium; b) beta: the emitted particle is an electron; c) gamma: it is a type of electromagnetic radiation that carries the excess energy of an unstable nucleus. 2) These nuclear reactions are due to the interaction of other particles or nuclei.

This paper proposes the use of nuclear energy by gamma decay, where the nuclei can present quantum states with discrete energy values. When it is at an excited energy level, it can pass to a lower level emitting photon of a certain frequency, therefore, the nucleus does not change its composition, but the nucleons experience a transition between two energy levels considered packets of energy emitted from the radioactive nucleus upon decay.

Equation 1 shows that the emitting nucleus (X^*) and the resulting child (X) have the same atomic

$$ {}^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma. \quad (1) $$

number (Z) and mass number (A).

Figure 2 shows that when a nucleus is at an excited energy level, it passes to a lower energy level.

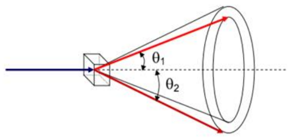
SPDC effect (spontaneous parametric down conversion): It is an optical effect of dipolar polarization, quadratically dependent on the electric field and incident photons in a nonlinear crystal can be converted into two photons. It is said that it is spontaneous because there is no input signal or inactive field that stimulates the process, but it is generated inside the glass spontaneously, its process is parametric because it depends on the electric fields, thus, there is a relationship of the input and output fields (Fig. 2).

Fig. 2: Gamma Decay.

The down conversion refers to the fact that the signal and idle fields always have a lower frequency than the pump. Thus, SPDC is a phenomenon that requires interactions between photons and crystals between the three photons within a uniaxial crystal, where the photon of the pump is partially or totally polarized in an extraordinary direction relative to the optical axis of the Crystal [16].

The SPDC effect is divided into two types: i) Type I, if the emerging photons leave perpendicular to the optical axis, ii) if one of the emerging photons leaves in the direction of the optical axis is said to be extraordinary and the other photon leaves in an ordinary way, that is, parallel to the optical axis and is known as Type II [17].

The SPDC effect is suitable for producing photons that are both correlated and overlapping. For Type II, the protruding photons are superimposed where the cones intersect, because polarization at that point is uncertain, see Fig. 3.



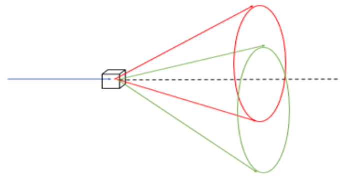


Fig. 3: Parametric conversion Type I (left) and Type II (right)). Adap

Because this is a non-resonant process, the generated photon can be emitted over a wide range of wavelengths, under phase adjustment conditions.

Based on the above, the proposal on the use of nuclear radiation as an energy source for the operation of the CubeSat satellite is framed within the SPDC effect (Spontaneous Parametric Down Conversion) in the representation of interaction in quantum mechanics and considering the First-Order terms in perturbative theory [19].

II. METHODOLOGY

First of all, it is necessary to know how solar energy operates to supply the electrical system of the satellites, knowing its location and time in the time of umbra,

The mission to be implemented will have a specific orbit and according to this, the time in which the satellite will not have illumination is calculated (Equation 2).

$$t_u = \frac{T}{2} - \frac{T}{\pi}\cos^{-1}\left(\frac{R_T}{R_s}\right) \qquad (2)$$

where R_T is the radius of the Earth, R_s the radius of the orbit of the satellite and T the orbital period.

In addition to calculating the time at which the satellite will not have illumination, it is also necessary to calculate which faces of the satellite are exposed to the sun and for how long.

Fig. 4 shows how the satellite varies its position with respect to the earth, and how rotation affects the amount of radiation received by the satellite faces.

Power distribution designs depend on the characteristics of the sources and functions of the subsystem. The power regulation and control are divided into three categories: controlling solar panels, regulating bus voltage and charging the battery.

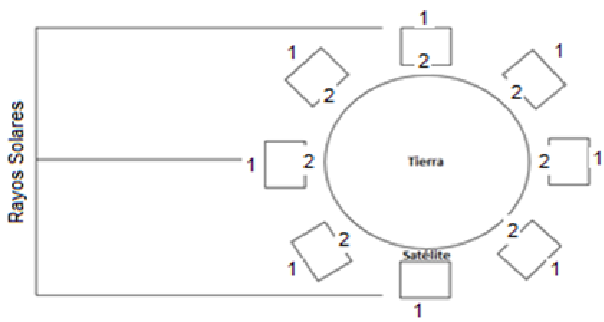


Fig. 4: Satellite with Face 2 facing Earth. Adapted from [12].

As it has been named throughout the paper, space missions require power to collect information and then transmit it to the earth. The supply that this requires is when solar cells are exposed to full or partial sunlight, during its rotation it enters the zone of shadow and umbra, at which time there is no supply of direct energy and its operation depends on the energy stored in the batteries and whose time depends on the height that is the satellite of the earth.

In order to determine the rotation time of the satellite, it is considered that the satellite has a uniform circular motion as shown in Fig. 5, being the LEO orbit, since the closer a satellite is to the Earth, the more circular its movement will be, where the variables of speed are related v= ((2π/T)/Rs) and the magnitude of the gravitational force Fg= G((MTMsat)/R2s) and centripetal force Fc=Msat(v2/R), with R_s the total radius or the sum between the radius of the Earth and the height at which the satellite is located and G is the gravitational constant whose value is 6.67 x 10-11 Nm2/kg2.

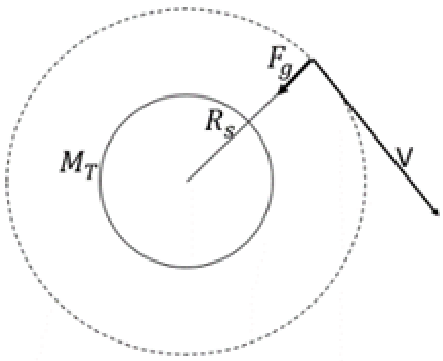


Fig. 5: Movement of the satellite in a LEO-type orbit.

To determine the period, the rapidity is replaced in the centripetal force equation by obtaining Fc=Msat (((2π / t)*Rs)2)/Rs, equating the forces results in the equation known as Newton's second law (Equation 3).

$$G\frac{M_T M_{sat}}{R_s^2} = M_{sat}\frac{\left(\frac{2\pi}{T}R_s\right)^2}{R_s}, \quad (3)$$

Canceling the radii, masses and clearing the period of the Equation (4) that defines the time it takes a satellite to make a single return to Earth, being this equation applied to any LEO type orbit, obtaining:

$$T = \sqrt{\frac{4\pi^2 R_s^3}{G M_T}}. \quad (4)$$

As mentioned, the orbit is circular, and the motion is uniform which is why the equation of the angular frequency given by the equation (5) is used.

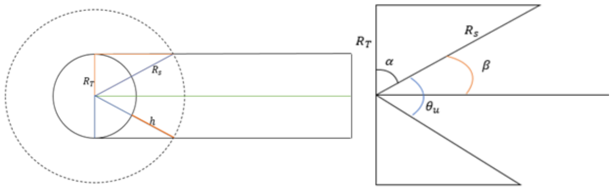
$$\omega = \frac{\theta_p}{t} = \frac{2\pi}{T}, \quad (5)$$

since this equation relates the umbra time to the period, the time is cleared by obtaining the equation (6).

$$t = \frac{T}{2\pi}\theta_p. \quad (6)$$

As observed in equation (6), the angle θp appears, which varies as the satellite changes position. This angle is due to the rotation of the satellite around the Earth and not on its own axis.

Fig. 6 shows the relationship of the radius of the satellite orbit defined by the sum of the radius of the Earth RT and the height above sea level h where the Sun would be located to the left of the figures. Figure a represents the motion scheme of a satellite around the Earth and Figure b is a zoom of the triangles formed in a.



a b

Fig. 6: Solar rays to define angle θ_u.

In Fig. 6b, it is evident that the angle θu or the angle of umbra, can be determined if the values of angles α and β are known. Because of the geometric shape of the radii, such angles can be calculated.

The first angle to be determined is α, this angle can be calculated using the trigonometric function of cosine, having the values of the adjacent catet and the hypotenuse, being α:

$$\alpha = \cos^{-1}\left(\frac{R_T}{R_s}\right). \quad (7)$$

Figure 6b shows that the sum of angles α and β is:

$$\alpha + \beta = \frac{\pi}{2}. \quad (8)$$

The next angle to be determined is β. To obtain this angle, the equation (7) must be replaced in (8), clearing the value of β, the following is obtained:

$$\beta = \frac{\pi}{2} - \cos^{-1}\left(\frac{R_T}{R_s}\right). \quad (9)$$

The last angle that appears in Figure 6 is the angle θu, as seen in the figure, this value can be calculated with the value of 2β, obtaining as a result the equation (10)

$$\theta_u = \pi - 2\cos^{-1}\left(\frac{R_T}{R_s}\right). \quad (10)$$

Substituting this umbra angle of the satellite in equation (6), the final equation of the umbra time for a satellite is given:

$$t_u = \frac{T}{2} - \frac{T}{\pi}\cos^{-1}\left(\frac{R_T}{R_s}\right). \quad (11)$$

Using equation (11), the time a satellite takes in the umbra is determined for some heights within the LEO (Low Earth Orbit) orbit which is between 160 and 2000 km above sea level, MEO (Medium Earth Orbit) between 10000 and 20000 km. For larger orbits, such as GEO and HEO, the calculation will not be performed since, being elliptical orbits, the equations of circular uniform motion are no longer valid.

To determine the values of the time that a satellite takes in the umbra, first the period is calculated using equation (4), knowing the value of the period and substituting it in equation (11), the umbra times for each height are obtained (Fig. 7).

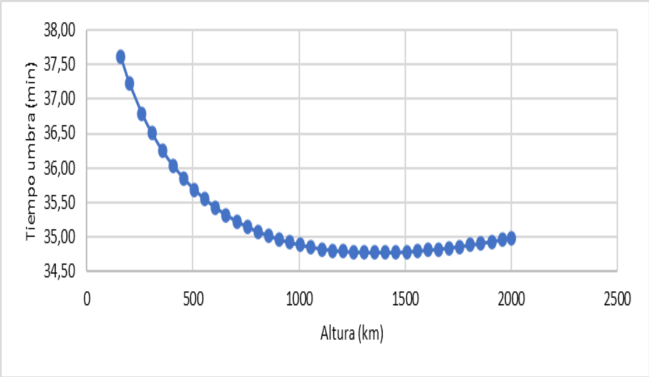


Fig. 7: Umbra time depending on satellite height.

As seen in Fig. 7 for heights less than 1400 km there is a variation in the time it takes a satellite to reach the umbra. For low heights, very close to the Earth, the time taken by the satellite in the umbra area is greater, due to the relationship between the speed with which the satellite moves and the distance travelled by it. In this case (Heights less than 1400 km), as the radius of the orbit approaches the radius of the Earth, the arc length describing the trajectory in the umbra decreases slower than the speed with which the satellite moves, causing the time in the umbra to increase. On the other hand, at heights above 1400 km there is an increase in the time of umbra, but this is because the satellite makes a slower movement. Although the time ratio of umbra to period is always lower.

This indicates that at higher altitudes the satellite has more exposure to The Sun, which in principle reduces the use of batteries.

Since the sun plays a very important role in the energy supply for the satellites and depends on the height at which the satellite is located, batteries will have to be used in order to continue the mission, which implies additional space on the satellite that can be used with better electronic devices. For this reason, the aim is to replace the sun and the batteries so that the mission is not affected by the umbra zone or, in the case of a probe, not to require the sun or batteries and to have a much longer duration.

As can be seen, the purpose of this device is to seek an alternative energy supply for a satellite, which is why it is important to know how a satellite works (CubeSat with its traditional structure), in what area the umbra is presented for each of the faces and how the power varies depending on the angle of radiation. For this, equation (12) was used, finding the power for each of the faces of the satellite.

$$P = A * \alpha * S * \cos(\theta) * \eta, \qquad (12)$$

where A is the area of the faces of the satellite, α the constant of the silicon panels (0.8), S the solar constant 1366 W/m2 and $\cos(\theta)$ represents the variation of solar incidence on each of the faces.

Results

Fig. 6 shows the flow diagram with the distribution of the results obtained by the proposed mathematical modeling.

Fig. 8, the flow diagram is observed with the process to be carried out to obtain the proposed mathematical modeling. The dotted line indicates an interaction in case it is desired to make use of other conditions to determine the nuclear material to be used.

For this purpose, nuclear material and a special layer containment are proposed, which, as mentioned above, seeks in principle to replace the sun and thus energetically supply the satellite no matter where it is located and allowing as far as possible to obtain space for other devices as they do not need batteries.

For this device to work properly, a spherical configuration is proposed, whose purpose is to provide an equal capture of the photons in all directions. Additionally, the configuration is by layers, where each layer will allow, initially, that the photons emerging from the nuclear material interact with the photovoltaic panel with an energy and a wavelength within the visible spectrum range, in order to transform the radiation into enough energy to supply the satellite as shown in Fig. 9.

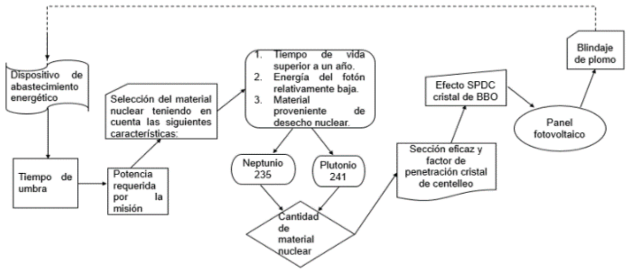


Fig 8. Flowchart of the proposed mathematical modeling.

Fig. 9: Proposed energy supply device for a satellite mission.

The first sphere, is the nuclear material, emitting gamma radiation, highly energetic photons, which has an operating range of 41nm to 700 nm, the nuclear material chosen must have a lifetime to supply the satellite energetically for more than a year, the material is sought to come from a nuclear waste, in order to make a contribution in the treatment of these materials.

The second sphere, is formed by a sparkling crystal, designed for the purpose of capturing highly energetic photons and emitting them by means of fluorescence due to the interaction of radiation with the crystal, with materials such as thallium doped sodium iodide (NaI (Tl)). The flash allows the decrease of the energy of the incident photon, giving as a result a close emission, if the photon does not interact with the matter or the output energy is higher than the reading range of the photovoltaic panel, a third layer is proposed to decrease the energy using another physical phenomenon.

The third sphere is a nonlinear optical birefringent Crystal, which has the function of decomposing a pumping photon in two, starting with a pumping photon that affects the crystal and when emerging from the crystal it is divided into two photons by means of the SPDC effect that comply with the principle of conservation of momentum and energy. One of the most used is the beta Barium Borate (BBO), whose characteristics help to present a higher probability of photon division and its operation range is a little higher compared to the other birefringent crystals.

The fourth sphere, is a photovoltaic panel, which has photoelectric effect that converts radiation into electrical energy and is distributed to each element of the satellite and maintains its optimal functioning, it should be considered that these panels are inverted compared to their usual disposal.

This nuclear material is intended to meet the following considerations: (1) that the Half-Life of the selected nuclear material is at least one year and (2) that such material may be nuclear plant waste. The calculations presented below are divided taking into account the path that the photon must take from leaving the nuclear material to interacting with a photovoltaic panel.

The first part of the calculations is to determine the amount of nuclear material needed to supply the satellite. Taking into account the above considerations, a search was made in the database of possible isotopes nuclear materials finding two that meet these characteristics. The first of these materials is neptunium 235, an isotope of neptunium 237, a synthetic element of the actinide family, with a Half-Life of 396.1 days and a radiation energy of 99,279 keV. The second material to be considered is plutonium 241, isotope of plutonium 244, which is a synthetic material, with a Half-Life of 14.35 years and a radiation energy of 100.95 keV.

Taking into account these two possible elements, the amount of material needed to generate a power of 60 W was calculated, this being the power generated by a 12U CubeSat

Based on the 60 W power, calculate how much nuclear material is needed to power the satellite using the equation (13)

$$N = \frac{P * \tau}{E}, \tag{13}$$

where P is the power required by the satellite, τ is the Half-Life Time of the nuclear material and E represents the energy of the gamma photon from the nuclear material.

The amount of material required by the mission taking into account the two nuclear elements results in 51.49 g for neptunium 235 and 695.26 g for plutonium 241.

Once the amount of material needed to supply the satellite is obtained, the calculation of the effective section is carried out, which gives an idea of the probability of interaction of the radiation with the matter and of what type this interaction is, by means of the photoelectric effect, Compton or creation of pairs [20].

As mentioned before, the device is composed of layers, each of them has a defined thickness, which makes the calculation of the total size of the device relevant.

To perform this calculation, the volume equation V=m/p is used, where m is the mass and p is the density. This value must be calculated for each of the spherical layers of the device, taking into account the values obtained. The total radius r of the device is calculated by equation 14, where r is the inner radius of each spherical layer. Taking into account the above equations, a final radius of 2.31 cm is obtained for neptunium 235, where the diameter is 4.62 cm. Performing the same calculation for plutonium 241, a final radius of 2.72 cm is obtained, where the diameter is 5.43 cm.

$$r = \sqrt[3]{\frac{3V}{4\pi} + R^3} \tag{14}$$

III. DISCUSSION

According to the research in the course of this paper, the BBO glass layer is a very interesting proposal that would help to improve the supply of satellites, but there are still shortcomings in the development of birefringent materials so that its application in aerospace developments is feasible in every aspect and not only from the theoretical point of view.

A solution to this would involve technological advances and reduced costs in birefringent crystals in the same way as has been advanced with photovoltaic cell technologies [21].

IV. CONCLUSIONS

In the present paper, the viability of changing from a system of energy supply by means of solar radiation to the use of nuclear material as an alternative energy system is demonstrated. In this paper, improvements and optimization in space missions for CubeSat satellites are proposed, showing that there is no restriction with respect to their size, which implies gains in missions that use the same physical volume of the satellite. In this way, sufficient material is presented for the prototyping phase.

Based on the foregoing, the amount of nuclear material required to supply the satellites with energy depends on the power required in the mission and the type of radioisotope employed. Keep in mind that the material required, with a power of 60W, can be neptunium 235 and plutonium-241, these being produced in an artificial manner and with a useful life greater than one year, for these two radioisotopes and under the condition of 60 W of power, is that the mission requires approximately 52 g of neptunium-235 or 696 g for plutonium-241. This indicates that neptunium 235 would offer both mass and volume savings.

Based on the proposed concentric spherical energy supply, it would enable the satellite to be energetically supplied throughout the mission, in addition to its material obtained from nuclear waste, it would lead to savings in the cost of purchasing batteries and it would have constant energy due to the radiation of the material and the conversion of the radiation due to the photovoltaic cells [22].

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