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A New Model Inspired by the Pompeii Worm to Reverse Overheating in Nanosatellites

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"Those who are inspired by a model other than Nature, a mistress above all masters, are labouring in vain."
attributed to Leonardo DaVinci

Nanosatellites are exposed to extreme temperatures on the spacecraft surface, which can reach up to ±100 °C. In this paper, we suggest a novel solution to this challenge by the use of biomimicry. The imitation of the behavior of living creatures in nature is an attempt to understand and synthesize a natural object or phenomenon in an abstract or concrete form. This inspiration from living things in nature can come through the materials, processes, or designs we see around us, and there is no engineering effort involved. In nature, the best example of temperature reversal is the Pompeii worm. The Pompeii worm realizes the conversion of the excess heat it is exposed to into cooling inside a multilayered tube. In this work, inspired by the strategy of the Pompeii worm in reversing overheating, we present a new model for the overheating problem in nanosatellites.

Introduction

Small satellites, also called micro-, nano-, and even picosatellites, have become increasingly popular. Since small satellites have a small surface area, cooling is a problem. In this article, we propose a solution based on the biological strategy inspired by the Pompeii worm (*Alvinella pompejana*).

Biological strategies have always been used as inspiration for innovation [1]. The term biomimicry has been defined and described in different ways by different authors. Hayes et al. [2] describe it as a field that "looks to biology and ecology to identify natural models that can inspire design and engineering solutions" [2]. ElDin et al. [3] describe it as a "science that seeks sustainable solutions by emulating nature's time-tested 3.8 billion years of patterns and strategies" [4]. Lurie-Luke [4] calls it a "field that seeks to interpolate natural biological mechanisms and structures into a wide range of applications" [4].

Nature has an enormous pool of inventions that have passed rigorous tests of practicality and durability in changing environmental conditions. To make the best use of nature's capabilities, it is critical to bridge the fields of biology and engineering and to see the collaboration of experts from both fields. This bridging endeavor can help transform nature's capabilities into engineering capabilities, tools, and technologies [5]. Drawing inspiration from biological strategies is understanding the basic principles of a biological process or adaptation and then adapting these concepts for bio-inspired product applications or to solve specific technical challenges [4].

Biological strategies have already turned out to be useful in the aerospace industry [4,6,7]. Ayre [6] points out areas identified by ESA to be particularly apt for using biomimetics. Protecting satellites from heat does not seem to fall into any of these categories but the author does point out that there are many other possible areas where biomimetics could play a part.

Many living systems function best within specific temperature ranges. Temperatures higher or lower than that range can negatively impact a living system's physiological or chemical processes, and damage its exterior or interior. Living systems must manage high or low temperatures using minimal energy, which often requires controlling responses along incremental temperature changes. To do so, living systems use a variety of strategies, such as avoiding high or low temperatures, removing excess heat, and keeping heat inside. The Pompeii worm is a great biological model for translating its long-term adaptation to high temperatures into cooling.

A Brief Look at the Structure of Nanosatellites

During 1957 and 1958, when the space age began, 3 small satellites, Sputnik-1, Explorer-1, and Vanguard-1, were launched into low Earth orbit [8]. Sputnik-1, the first satellite sent into space, weighed just 83 kg. Explorer-1 was 14 kg. The obvious reason for the small size of the satellites in this time was the low capacities of the launch systems [9]. Since then, the launch capacities have increased dramatically and satellites have increased in size and mass.

Today, however, progress in hardware technology has made it possible to cram more instruments into a smaller volume, which has made it possible to again decrease satellite size and thus the price of launching them into space.

Compared to conventional large satellites, micro/nanosatellites have a shorter development cycle, lower cost, and more flexible system implementations [10]. The massive deployment of microsatellites is recognized and explained by the reasonable cost, short detailing time, and possibility to include complex devices such as multifunctional equipment and optical systems as payloads. Small satellites are classified into the following conditional groups (Fig. 1): nano- and picosatellites (<10 kg),

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microsatellites (10 to 100 kg), minisatellites (100 to 500 kg), and interplanetary small missions (>500 kg). The limited mass and power in microsatellite designs, the specific constraints induced by the payload, and the specific volume for the cleaning systems produce a set of requirements for each satellite system as well as the thermal control system. Investigation of the thermal tools used in practice in microsatellite designs, real thermal schemes, and components can be useful to better address this issue [11].

In recent years, there has been an increasing growth in the small satellite sector, especially nanosatellites (1 to 10 kg). The widespread use of nanosatellites with their low cost has encouraged commercialization [12]. The increase in the number of nanosatellites in the last 20 years is generally divided into 3 phases. A relatively slow growth can be observed from 1999 to 2013. From 2013 to 2016, there is a noticeable increase as projects started in 2008 to 2010, including the first demonstrations of the constellations, begin to be launched. Since 2017, the growth has accelerated even more. As of 2022 1 August, 2,068 nanosatellites had been launched [13].

The structural subsystems of nanosatellites hold the other subsystem components of the vehicle together and protect them against harmful effects from the external environment. For this reason, the most important step in the design process of nanosatellites is material selection. The materials used in nanosatellites should be selected according to their material properties, taking into account their usage areas. With the use of the right material, both resistance to structural loads and protection against radiation, high temperature difference and vacuum conditions in the space environment can be provided.

Various materials such as aluminum, titanium, graphite composite, and composite sandwich panels are used in the manufacture of nanosatellites. These materials differ in cost, manufacturing process, mass, strength, durability, and labor required [14]. The materials used in the manufacture of nanosatellites must provide protection against radiation and extreme temperatures, in short, against the dangers that may come from the outer space environment. This study focuses on the extreme temperature hazard faced by nanosatellites in the outer space environment.

Overheating in Nanosatellites

Nanosatellites are a growing space industry segment and the thermal cycle is an essential part of every nanosatellite. One of the challenges for space applications is the low-temperature operation. In orbit, the spacecraft surface experiences extreme temperature fluctuations, which can reach up to ±100 °C [15]. Providing thermal control of satellites plays an important role in determining the performance and functionality of the satellite in orbit [16]. The main purpose of the thermal design of a nanosatellite is to keep all the elements of the satellite within the specified temperature ranges (Table). Satellites are exposed to heat from both the Sun and Earth. There must be heat dissipation between parts of each element on the satellite [17].

Miniaturized satellites are densely packed within the smaller satellite volume due to high-power components and payloads, resulting in thermal problems as the available radiative surface area is reduced. For high-power, scientific, and cryogenic small satellite missions, solving thermal challenges is imperative. Earth exploration missions using small satellites are now conducted using nano/microsatellites and are expected to grow exponentially. Earth observation refers to the use of remote sensing technologies to monitor land, sea, and atmosphere. Most Earth observations are made in the infrared region of the electromagnetic spectrum. Infrared detectors designed to operate at wavelengths in the 0.76 to 103 μm range require cooling to perform better. The dark current is important reduced when operating at low temperatures and therefore most infrared detectors need to be cooled to lower temperatures for certain applications. The low temperature requirement becomes extremely important for detectors operating in the cryogenic temperature regime [18].

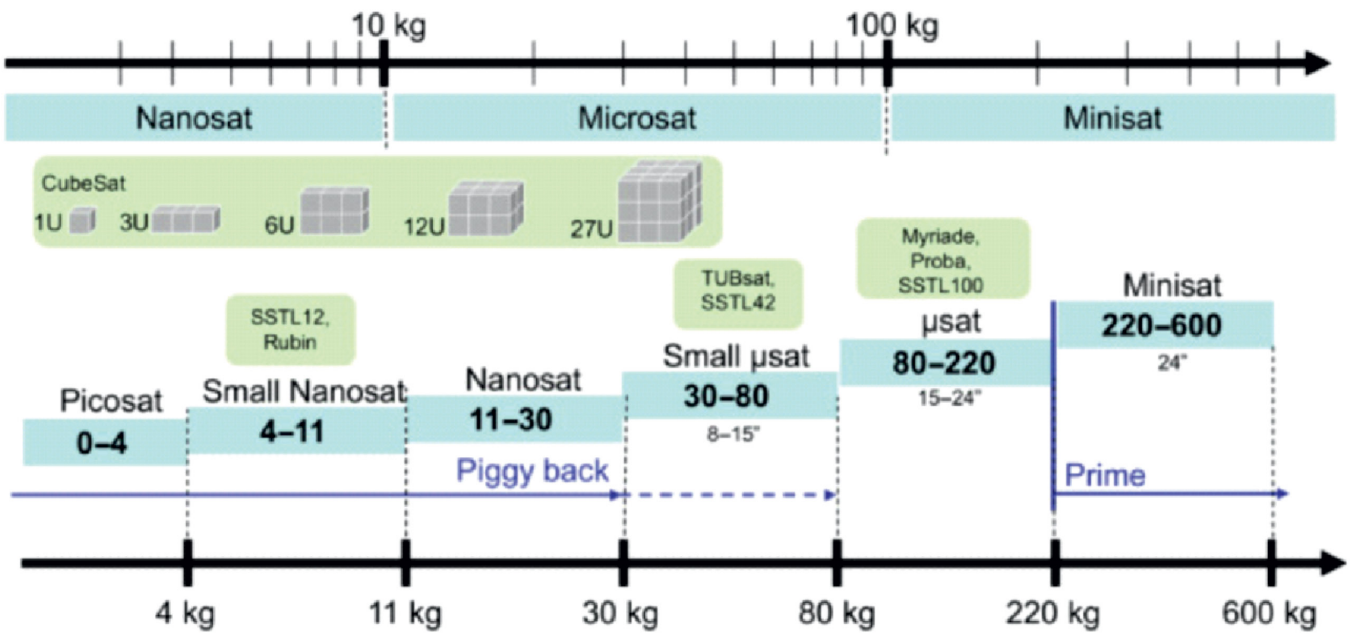


Fig. 1. Evolution of satellite mass and emergence of new sweet spots. Picture courtesy of Denis, G.; Pasco, X.; Pisot, N.; Texler, D.; and Toulsa, S. Source: [55].

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Biology and Physiology of the Pompeii Worm (*A. pompejana*) as a Biological Model

A. pompejana, commonly known as the Pompeii worm [19], is an annelid worm (Fig. 2) that lives exclusively at deep-sea hydrothermal vents (sometimes referred to as "chimneys") in the Pacific Ocean.

These chimneys are geological formations where the waters coming from the depths of Earth's crust and heated to temperatures high above the boiling point at the depth in question (109° C) by the effect of magma mix with the ocean waters. Pompeii worms have been seen to live in the ocean at a depth of about 2,600 m [20,21]. They face extreme environmental conditions, including high temperature and pressure, as well as high levels of sulfur and heavy metals.

A. pompejana is a small annelid about 10 cm long and less than 1 cm in diameter [22]. To cope with high temperatures, Pompeii worms have evolved adaptations that include a stable glycoprotein matrix and a protective tube/cocoon made of positively and negatively twisted polymer layers containing elemental sulfur, a number of heat shock proteins, and stress oxidative enzymes. These worms remain stable and active at temperatures above 50 °C [23] and the tubes insulate the worms from high temperatures [24,25].

Table. Operating temperature ranges for satellite elements.

Component	T_{min} (°C)	T_{max} (°C)
Main structure	–40	+85
Solar cells	–100	+100
Electronics	–20	+60
Battery	–20	+40

Source: [17].

The Pompeii Worm Strategies for Adaptation to Extreme Temperatures Under the Sea

Adaptations of organisms to extreme temperatures and conditions such as extreme cold can be very diverse. Biologically, it is easier for organisms to adapt to chemical extremes than physical extremes such as temperature and high pressure [26].

Temperature is one of the most important environmental factors governing the distribution of a species [22]. Adaptation to cold is usually associated with reduced heat tolerance [27]. Some highly specialized prokaryotes can grow at temperatures above 113 °C, but eukaryotes appear less versatile and do not normally occur above 55 °C. Many worms living in deep-sea hydrothermal vents seem to live at temperatures of about 80 °C [22]. Active deep-sea hydrothermal vents typically contain high-temperature flow areas (above 300 °C) that are essentially abiotic. Associated with and around these warm regions are regions of cooler (below 100 °C) diffuse flow where mixing with ambient seawater (2 °C) occurs [28]. The Pompeii worm is currently considered the most thermotolerant eukaryote on Earth, despite the largest known thermal [29] and chemical ranges, whose transcriptome has recently been sequenced [30]. A desert ant tolerates a temperature of 53.6 °C [31]. An average upper thermal limit for insects was assessed between 44.4°C and 47.4°C [32]. Simple eukaryotes such as fungi or algae grow at temperatures of about 55 to 60 °C [33]. The Pompeii worm, on the other hand, can withstand temperatures as high as 105 °C [34–38].

Pompeii worms live in the warm parts of hydrothermal ecosystems of active vents during the East Pacific Rise from 21°N to 32°S [22]. In this environment, pressures usually reach 260 bar and temperatures reach 350 °C. In addition, hydrothermal



Fig. 2. *Alvinella pompejana*: the animal outside its tube showing the white filamentous epibionts (left) and inhabited tubes covering a smoker wall (right). Pictures courtesy of Le Bris, N. and Gaill, F. Source: [44].

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fluids are rich in acidic, anoxic, and metallic sulfides [39]. These metal sulfide precipitates form black smoke and the smoke creates large vents [28,40]. Pompeii worms oscillate between nutrient-rich hot water and oxygen-rich cold water. This action also mixes the cold water into the tube, but more importantly, a fleece-like bacterial layer helps insulate the Pompeii worm from the extreme heat. Bacteria in the outer tissue of the Pompeii worm contain sulfur granules [39] and metallothionein-like proteins. Also, there are high concentrations of zinc, arsenic, and sulfur in different epidermal areas of the worm [41]. The Pompeii worm can only tolerate temperatures as low as 55 °C on its own, but bacteria in the hairs covering its body circulates cold water over the outer body and dissipates heat. The bacteria not only help regulate the worm's temperature, but also break down minerals in aeration to aid their hosts [42,43]. Experiments carried out by Le Bris et al. [44] demonstrated that *A. pompejana* influences mineralization processes at the interface between the smoker wall and the ambient oceanic water. The study also indicated that *A. pompejana* exerts a primary control on its environment by structuring the thermal and chemical gradients, creating a mosaic of micro-environments by the construction of protective tubes. The supply of water through the tube prevents exposure to the extreme temperature spikes and high sulfide concentrations. Circumventing the large erratic changes generally associated with hydrothermal venting, *A. pompejana* tubes create more homogeneous chemical and thermal microniches and likely play a role in microbial diversity.

Protective Tubes as a Strategy against Hot Ventilation Liquids

The extracellular matrix of Pompeii worms consists of 2 different tissues. These 2 different tissues are the exoskeleton of the creature and the tube that allows the worm to settle on the chimney walls, and the collagen that forms the main molecular component of the tissues covering the body of the worm [45]. Collagen is one of the best-known extracellular proteins in the animal kingdom and is a relevant marker of thermal adaptation. Its stability is critical to animal survival in controlling deformation of the body wall by hydrostatic pressure [45]. The temperature at which the collagen molecule is denatured is 46 °C for the cuticular collagen lining the animal epidermis and 45 °C for the interstitial found in worm tissue. The level of thermal stability of the Pompeii worm cuticular interstitial collagen is importantly higher than that of other ventilated annelids [46].

The most remarkable adaptation of the Pompeii worm relative to other alvinellid species is in this tube [45]. Tubes insulate worms from high temperatures [24,25]. Pompeii worms have developed adaptations to cope with high temperatures, including a glycoprotein matrix and a series of heat shock proteins in tubes made of positively and negatively twisted polymer layers containing elemental sulfur, and stress oxidative enzymes that remain stable and active at temperatures above 50 °C [23].

The material that makes up the tubes of Pompeii worms is an anterior-ventral granular shield [47]. Most of the material that makes up this shield is homogeneous granules secreted by deep mother cells. Although the organic material of the tube is granules, the other 7% consists of hexose sugar, which is an oligosaccharide material. The tube consists of a concentrically multilayered fibrous structure in which overlapping layers of parallel fibrils change direction from one leaf to the next. The

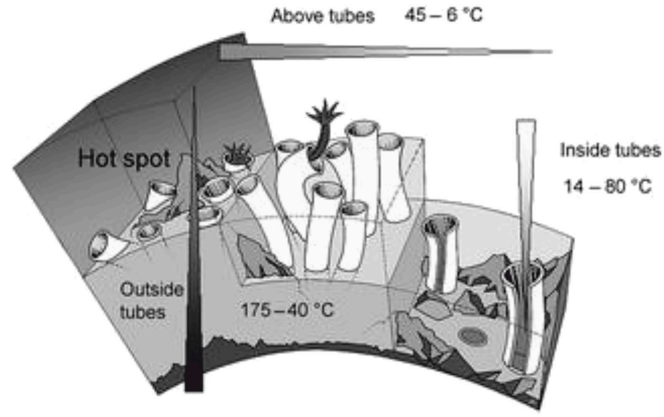


Fig. 3. Diagram of the Pompeii worms' colony. Courtesy of Le Bris, N. and Gaill, F. Source: [44].

number and thickness of the layers are fixed. Layers differ between different parts of the tube [45].

The inner surface of the tubes is covered with filamentous bacteria trapped under successive layers of material. Each layer of the tube consists of sublayers, and each layer is separated by trapped bacteria. A new fibril distribution appears within the layers of secreted granules, reminiscent of the arrangement of polymeric units in a cholesteric liquid crystal [48]. With this secretion, called mucus secretion, bacteria can provide the constraint that determines the initial structure and is then replaced by the fibrous structure itself, as revealed, or by additional pulses of mucus production and bacterial growth. This type of biopolymeric organization is thought to provide a certain thermal resistance to the worm [45].

Minerals cover 29% of the tubes [20] and show certain patterns of association with tubes. Zinc-iron sulfide nanocrystals grouped into submicrometer-sized clusters consist of layers of proteinaceous tubes. These minerals show a special zinc-iron signature and have a conserved dimension, unlike mineral deposits found outside the pipes. This acts as an effective barrier to the tube's external environment [49]. The dense filamentous bacterial coating on the inside of the tube is not uniform. Bacteria may be absent in some areas, resulting from the difference in secretory activity of the worm's epidermis [45]. Tubes of Pompeii worms do not contain chitin. The material of the tube has significant chemical stability. Alvinella tubes react little to these or to disulfide bond-breaking agents, although a cycle of concentrated hydrochloric acid and potassium hydroxide treatments causes delamination, swelling, and some dissolution. Thermal stability is also excellent, with little swelling or shrinkage in the 0 to 100 °C temperature range [20].

Figure 3 is a colony diagram of Pompeii worms. In the upper seawater layer, temperature and pH vary with local fluid outflows. Within the thickness of the colony, the tubes are surrounded by a matrix of mineral and organic sediments. Undiluted acidic hydrothermal fluids circulate in this matrix. The inside of the tubes is mainly seawater, heated by thermal conduction, and enters the tubes through their openings [44].

Design Inspired by the Pompeii Worm for Reversing Overheating in Nanosatellites

Satellites traveling at various altitudes around Earth move in and out of Earth's shadow in the orbits they follow and are

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therefore exposed to extremely large temperature differences. Cyclically repeated temperature changes can cause damage to satellite structural subsystems. Therefore, there are different designs for reducing the thermal cycle of nanosatellites. Li et al. [50] mention the inclusion of a heat source mounted directly on the deck. The threshold can be extended to 100 W/m^2, which can be calculated by rule number analysis. Bulut et al. [51] state that the entire surface of nanosatellites should be covered with solar cells. Tuttle et al. [52] suggest a simple thermal belt containing a thermal switch that can be retroactively attached to a nanosatellite and that can provide a significant temperature drop. According to Rossi [53], optical coatings are a simple passive solution that does not add large masses to the satellite design and should be the first choice for thermal control. A secondary option is multilayer insulation with no electrical requirements. In addition to these solutions, active thermal management solutions can be considered. Heaters are a simple active solution that may be required within the subsystems of nanosatellites and can be easily integrated when a passive solution cannot be found.

In contrast to the above examples, we were inspired by the Pompeii worm as a biological model for handling the problem of overheating in nanosatellites. The Pompeii worm is extremely successful in reversing overheating. Figure 4 is a schematic of the thermal protection cone of the Pompeii worm.

Pompeii worms form U-shaped multilayered proteinaceous tubes on the surface of zinc sulfide diffusers and in a few cases in the walls of black drinkers [35]. The front ends of the tubes are radially oriented, giving the smoker walls a feathery appearance. The diameter of the tube increases forward to a maximum of 2 cm. The outer surface of the anterior end is usually scaly, and the tube opening is either cylindrical or funnel-shaped, sometimes with a transverse septum separating the 2 associated tubes [54].

Figure 5 is a technical drawing of our nanosatellite model. Figure 5 shows the body of the nanosatellite, which consists of the top cover, side covers, and bottom covers. In the center of the top cover in Fig. 5, there is a mouth section where the protective equipment will be placed. There are also material-saving cavities to reduce cost.

On the side covers in Fig. 5, there is a channel stabilizer to fix all covers to each other, electronic card slots, and screw holes to fix electronic cards. There are also ventilation holes on the side covers to provide air circulation. The flat plate in Fig. 5 is the bottom cover.

Figure 6 is our model inspired by the warming reversal strategy of the Pompeii worm in Fig. 4.

The superiority and difference of our nanosatellite model compared to existing techniques and designs are the multilayer internal equipment protective funnel to be placed inside the nanosatellite. In Fig. 6, the multilayer internal equipment protective funnel does not fully penetrate into the nanosatellite. The top cover of the nanosatellite has a funnel exit hole that leaves the end of the funnel outside. This protective equipment is positioned so that the bottom part protrudes into the inner surface of the lower lid and the top part protrudes into the opening in the center of the upper lid. In this way, it protects the electronic equipment inside the body from cold and hot ambient conditions and ensures thermal heat balance between the layers. The main purpose of the multilayer internal equipment protective funnel is to prevent external heat from passing into the layers and to ensure that the equipment of the nanosatellite is not damaged. The multilayer internal equipment protective funnel can maintain the thermal balance at a constant level. The protective equipment is designed in the form of a funnel, inspired by the Pompeii worm, narrowing toward the top cover. However, alternatively, it can also be produced in cylinder form.

Conclusion

The problem of thermal heat in the outer space environment has always been among the most important problems of nanosatellites. The Pompeii worm represents an excellent biological model due to its long-term adaptation to high temperatures, its efficiency, and its sustainability. The Pompeii worm has developed structural adaptations to survive in harsh environments. The tubes in which the Pompeii worm lives act as insulators, isolating it from heat and cold. The layering of the tubes is the most important factor in reversing temperature. Inspired

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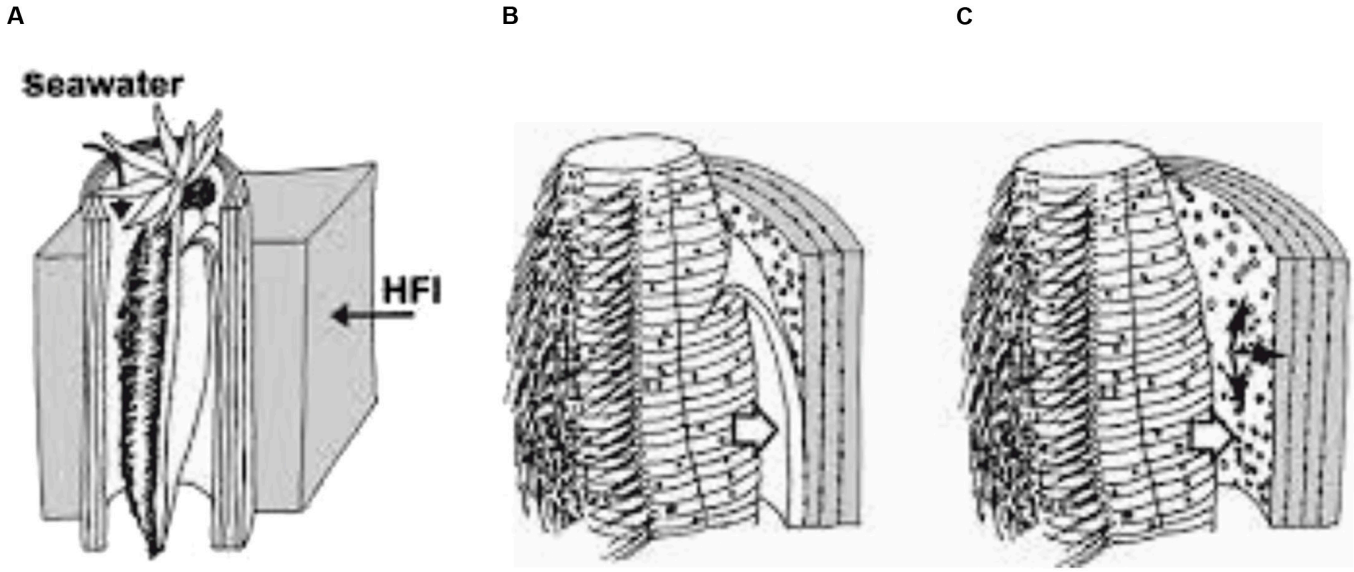


Fig. 4. Schematic of Pompeii worm thermal protection cone. Image courtesy of Zbinden, M.; Martinez, I.; Guyot, F.; Cambom-Bonavita, M.A.; and Gaill, F. Source: [49].

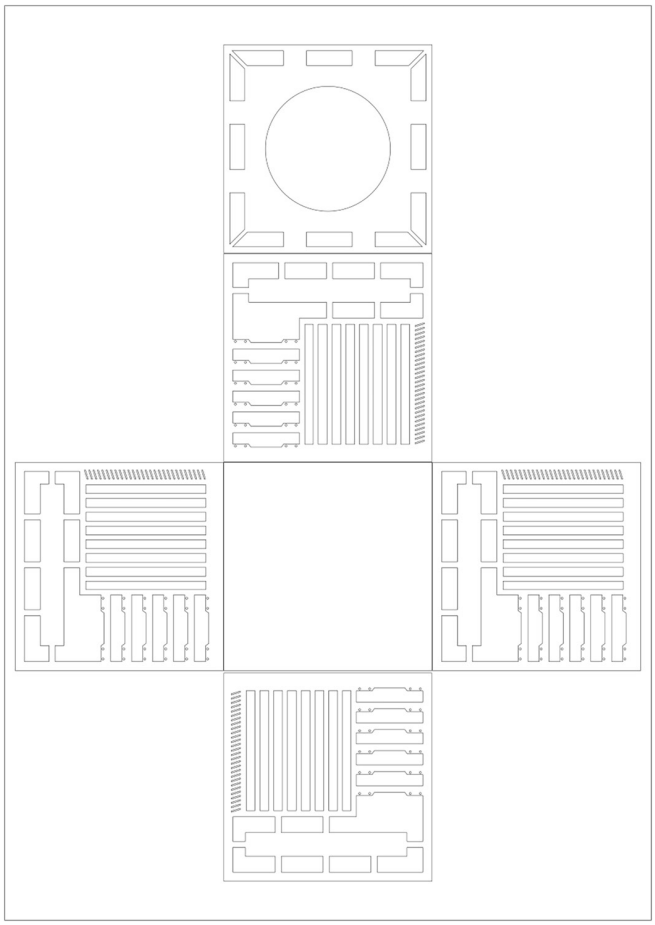


Fig. 5. Technical drawing of the nanosatellite. Image by the authors.

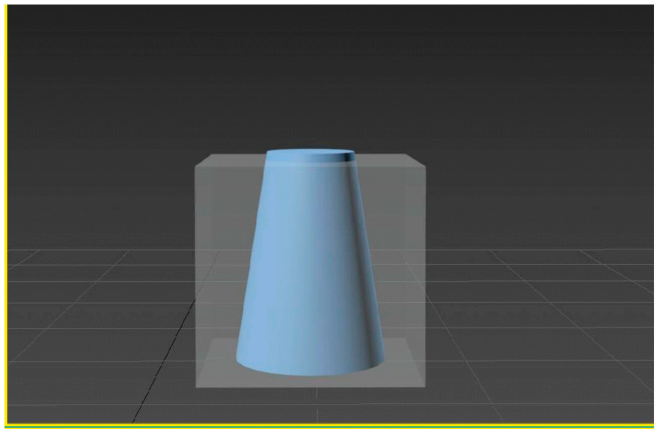


Fig. 6. Schematic of the thermal protection device for nanosatellites inspired by the thermal protection cone of the Pompeii worm. Image by the authors.

by the Pompeii worm, this new nanosatellite model, which we have developed, differs from other satellites in terms of design and technical aspects, namely, the multilayered internal equipment protective funnel placed inside the nanosatellite. This multilayered funnel provides thermal stability to prevent damage to the internal equipment. The new nanosatellite model can be a new alternative for the rapidly growing space industry.

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Data Availability

No data has been shared in this review article paper.

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