Review Article

The Potential of Aerogels for Orbital Debris Remediation

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ABSTRACT

The issue of orbital debris has become increasingly critical, particularly with the rapid expansion of satellite constellations like SpaceX's Starlink and Amazon's Project Kuiper. These initiatives are expected to significantly increase the number of CubeSats in Low-Earth Orbit (LEO), substantially raising the risk of orbital collisions. As Earth's orbit becomes increasingly congested, the threat of Kessler syndrome—a cascade of collisions generating more debris—looms larger. To address this challenge, I propose a mission concept for orbital debris remediation using aerogel collector satellites. Aerogels are ultralight synthetic microporous materials that have demonstrated their efficacy in capturing high-velocity particles, as evidenced by their success in NASA's Stardust mission in 1999. Their unique microporous structure enables them to decelerate hypervelocity particles over a very short distance without fragmentation. This mission envisions deploying an emergency aerogel-based orbital debris collector in response to sudden debris surges, such as those caused by satellite collisions or anti-satellite missile tests. The proposed system involves a medium-sized, bus-shaped spacecraft equipped with a deployable aerogel shield. In its stowed configuration, the aerogel is compactly folded into a circular structure. Once in orbit, it unfolds to form a protective barrier positioned at the spacecraft's front. In the event of a debris-generating collision in LEO, up to 10 of these spacecrafts would be launched using Rocket Lab's Electron launch system. Once deployed, the satellites would navigate through the debris cloud, capturing as much material as possible. After approximately one year, the spacecraft would deorbit and re-enter Earth's atmosphere, allowing the collected debris to burn up upon re-entry.

Keywords: Space; Orbital debris; Aerogels; Sustainability; Safety

INTRODUCTION

According to the European Space Agency (ESA), orbital debris is defined as "all non-functional, artificial objects, including fragments and elements thereof, in Earth orbit or re-entering into Earth's atmosphere" (1). While large pieces of orbital debris such as old thrusters and booster stages are dangerous to spacecraft, even sub-millimeter debris can pose a serious threat to human spaceflight and robotic missions. Since 1999, the ISS has made 32 course corrections to avoid orbital debris, and 25 of these course correction burns have been in the past 15 years (2).

Despite the increasing risk orbital debris poses to future spaceflight, Earth's orbit continues to become more

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congested with satellites. Elon Musk's Starlink mega constellation plans to deploy nearly 42,000 satellites, a dramatic increase compared to the approximately 10,000 satellites currently in LEO, of which only 8,000 remain operational. To put this into perspective, the proposed total of Starlink satellites surpasses the number of regularly tracked pieces of orbital debris measuring between 5–10 cm, monitored by Space Surveillance Networks worldwide. The growing presence of Starlink satellites has already increased the frequency of collision avoidance maneuvers, highlighting the need for "intervention...to control the growth of space debris in low Earth orbit" (3). This rapid growth in orbital debris is partly attributed to the increasing frequency of space launches using non-reusable rocket boosters, such as the Atlas V and Vulcan Centaur. These missions leave both satellites and discarded booster stages in orbit, further contributing to the clutter. Collisions between satellites exacerbate the problem, potentially triggering a cascade of orbital debris. While reusable rocket boosters are becoming more common and therefore mitigate debris to some extent, even small fragments—ranging from flecks of paint to steel spheres, tenths of millimeters in diameter — can endanger spacecraft and satellites (4).

A notable example of such a collision occurred on February 10, 2009, when the Russian satellite Kosmos 2251 collided with the American satellite Iridium 33. This event generated nearly 2,000 trackable debris fragments (10 cm or larger) and hundreds of thousands of smaller, untraceable pieces. Similar debris surges have resulted from anti-satellite weapon (ASAT) tests conducted by Russia, India, and China, further exacerbating the problem in LEO. If left unresolved, the growing orbital debris population could jeopardize not only future human space exploration but also the continued operation of satellites critical for communication, navigation, and Earth observation.

Numerous solutions have been proposed to address this challenge, most focusing on de-orbiting debris and ensuring it burns up in Earth's atmosphere. Proposed approaches include magnetic manipulation of space junk, harpoons to spear debris, and drag augmentation systems. This research paper will focus on an innovative solution that has not yet been widely explored—using aerogels for orbital debris remediation.

The paper will examine the unique properties of aerogels and their manufacturing process, emphasizing why they are well-suited for this purpose. It will also outline a potential mission design incorporating aerogels to address the growing threat of orbital debris in LEO.

AEROGELS

Aerogels are among the lightest materials ever synthesized, with densities ranging from 0.0011 to 0.5 g/cm³ (5). These materials are microporous solids created by removing the liquid phase from their gel structure. While aerogels are most commonly synthesized from silica-based polymers, variants composed of alumina and titania also exist (6).

Aerogels have gained prominence in aerospace applications, particularly as thermal insulation on spacecraft, due to their very low thermal conductivity (Figure 1) (7). They have been used for this purpose on all the Mars rovers and the Space Shuttle insulation tiles (8). Their unique microporous structure not only makes them efficient insulators but also presents an innovative solution for orbital debris remediation.

Production of Aerogels

An aerogel is the solid framework of a gel, isolated after removing its liquid component. The most common method for producing silica aerogel involves mixing a

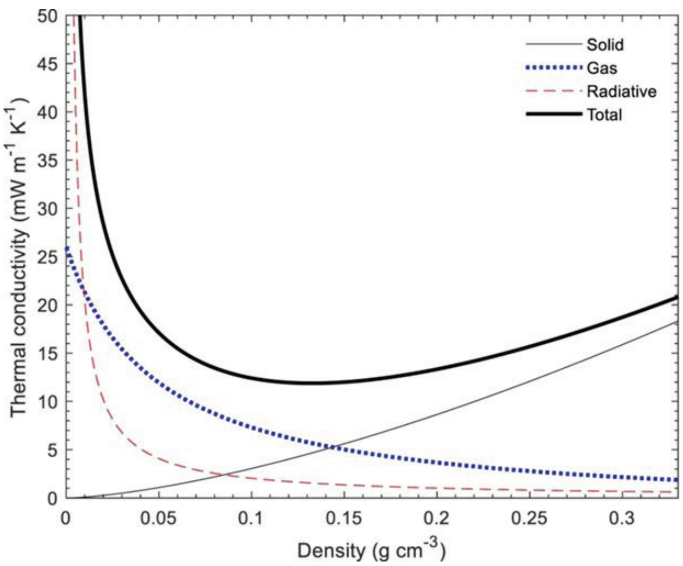

Figure 1. Principle profile of the temperature-dependent thermal conductivity and its components at ambient pressure and temperature. The data were calculated by assuming the following material parameters and boundary conditions: temperature $T = 300$ K, pressure $p = 1$ bar, $\lambda 0 = 140$ mW m^{-1} K^{-1}, a temperature independent $e^*(T) = 40$ m² kg^{-1}, $n = 1$, $\alpha = 1.5$, a skeletal density $\rho 0 = 1.280$ g/cm³, and a density dependent pore size calculated from the density for a specific surface area of 400 m²/g (7).

silicon alkoxide with water and a solvent, such as acetone or ethanol (9). Through a complex reaction between the alkoxide and water, silica nanoparticles are formed, which then aggregate to create a gel. To eliminate impurities, the gel is soaked in a pure solvent like acetone or ethanol. This purification step is often repeated over several days to ensure the gel is free of contaminants (10). The final solid product is obtained through supercritical solvent drying, typically using carbon dioxide. The process includes the following steps:

The gel is placed in an autoclave, where it is heated and pressurized to the critical point of the solvent—the temperature and pressure at which the liquid and gas phases become indistinguishable.

Excess gas is vented from the autoclave, and the process is repeated as necessary.

The final product retains the original porous structure of the gel, but all liquid has been removed.

Current State of Aerogels

Aerogel's unique properties make it highly effective at capturing debris particles traveling at hypervelocity speeds. When a hypervelocity particle collides with an aerogel, the particle disrupts the internal structure of the material, gradually transferring its kinetic energy into the mechanical energy of the aerogel and dissipating it as heat. The intricate network of interconnected nanostructures forces the particle to undergo thousands of microscopic "breakages," allowing aerogels to decelerate a hypervelocity particle from approximately 7.0 km/s (relative to the collector) to 0 m/s within milliseconds (6, 11).

Aerogels have already demonstrated their effectiveness in capturing hypervelocity particles during space missions. The Stardust mission, launched on February 7, 1999, became the first mission to safely return cometary samples from deep space to Earth. By flying behind the comet Wild-2, Stardust extended an arm equipped with 3 cm thick, three-layer gradient-density aerogel bricks. These aerogel bricks successfully captured comet particles traveling at velocities exceeding 6.1 km/s (12). Figure 2 illustrates the tracks left by particles upon collision with the aerogel (13). The size of the comet particles ranged from 0.1 - 100 micrometers in range (14).

Additionally, unlike other materials, aerogels maintain excellent structural retention after impacts with sub-millimeter sized debris. The orbital debris collector experiment from 1996-1997 placed low density silica aerogels on the Mir spacecraft to capture hypervelocity particles. While the experiment itself was not meant to test aerogel retention strength, the collectors amassed hundreds of particles and remained intact throughout the duration of the mission, thus showing the incredible retention strength of aerogels. The Large Area Debris Collector (LAD-C) was a proposed mission to mount a 10 m^2 aerogel collector on the ISS. While it was cancelled before it could be implemented, LAD-C was projected to capture particles in the centimeter range which highlights their flexibility, as well as their incredible retention strength to absorb numerous impacts from hypervelocity particles (15).

MISSION PLANNING

The proposed mission is designed for emergency situations where a significant volume of orbital debris is generated in a short period, such as during a satellite collision or an Anti-Satellite Weapon (ASAT) test. In such scenarios, a small prototype constellation of 10 spacecraft will be deployed to traverse the resulting debris cloud. Aerogel bricks, positioned on the fore section of each spacecraft, will capture as much debris as possible. After approximately one year in orbit, the spacecraft will deorbit and reenter Earth's atmosphere, ensuring the collected debris is safely removed from orbit. The debris captured will range in diameter from microns to approximately four or five millimeters in diameter.

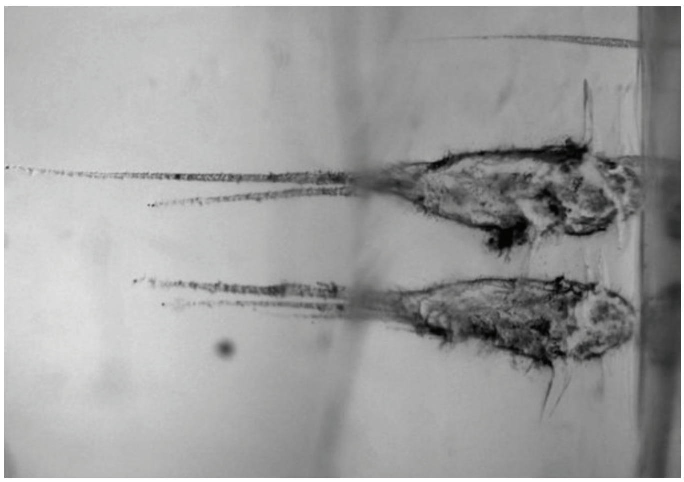

Figure 2. This image shows the tracks left by two comet particles after they impacted the Stardust spacecraft's comet dust collector. The collector is made up of a low-density glass material called aerogel. Scientists have begun extracting comet particles from these and other similar tadpole-shaped tracks (13).

Spacecraft Design

The spacecraft design for this mission is based on the Stardust spacecraft. The dimensions of the craft will be 1.6 m × 0.7 m × 0.7 m. The aerogel collectors will consist of 10 cm × 10 cm × 3 cm bricks with a 3-layer gradient density from 0.05 g/cm^3 to 0.1 g/cm^3. When in its folded position, the collector will be a circle with a radius of 0.6 meters (Figure 3) (16). The ratio between the folded and unfolded structure is approximately 1:9 (16). Thus, the unfolded diameter will be 5.4 meters (Figure 4). The craft will then fly through the cloud of debris at a certain inclination, collecting as much micro-sized orbital debris as possible. For maneuvering, the spacecraft will have four cold gas thruster rockets, one on each bottom vertex of the cuboid. These will ensure the spacecraft attain the correct orbit and do not collide with other large pieces of debris. Additionally, to prevent destabilization, the spacecraft will have an Attitude and Orbit Control System inside its body. This will control four additional reaction control thrusters on the midpoint of each long edge of the spacecraft; these manage the orientation, yaw, pitch, and roll of the spacecraft.

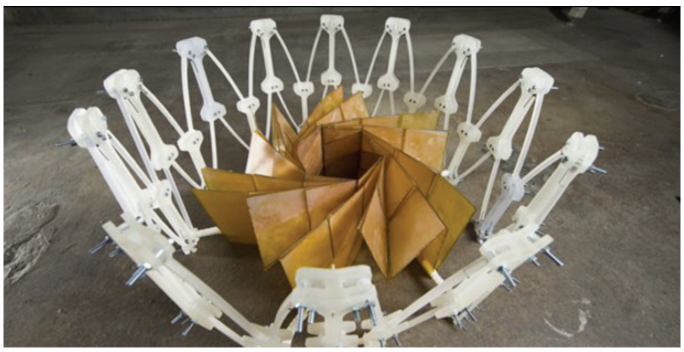

Figure 3. Researchers at NASA's Jet Propulsion Laboratory, Pasadena, California, and Brigham Young University, Provo, Utah, collaborated to construct a prototype of a solar panel array that folds up in the style of origami, to make for easier deployment.t Image copyright BYU photo (16).

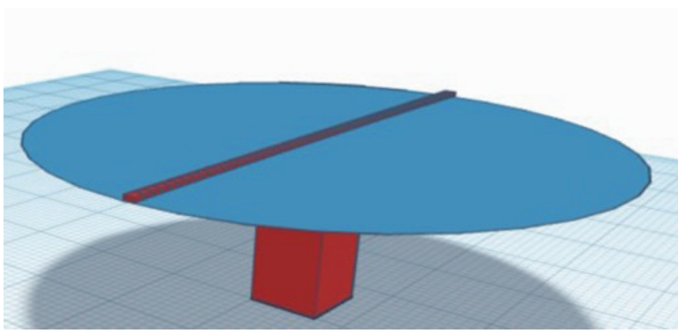

Figure 4. 1:1 scale CAD design of the entire spacecraft in TinkerCad with one row of aerogel bricks colored in red (other rows of aerogel omitted for simplicity).

To protect the collection system during launch, a small circular door will be placed over the folded collector. The rough mass of the entire spacecraft will be approximately 300 kg, which is based on the mass of Stardust, but this spacecraft will not have as many scientific instruments or non-deployable solar panels and thus will be much lighter than Stardust (17).

Mission Design

Predicting the exact trajectory of debris following a collision is inherently difficult due to the various influencing factors, including whether the event is caused by an explosion, an Anti-Satellite (ASAT) weapon, or a satellite-to-satellite collision. In particular, for ASAT events or collisions, the inclinations of the two bodies will be different. As such, there would be two clouds of debris centered around the inclinations of the two original objects. For this research, the intention is to focus on the debris from a single object and take as reference the Indian ASAT test, Mission Shakti, conducted in 2019. According to Yu Jiang, the debris cloud produced by this test led to the observation of secondary debris. Overall, Yu Jiang's research showed that the number of fragments created from the ASAT was larger than 0.0018 meters approximately 2.18×10^5. Therefore, the number of potentially dangerous fragments resulting from India's ASAT test was also expected to exceed 2.18×10^5 (18).

Figure 5 illustrates the modeled trajectories of the orbital debris in this experiment. The debris exhibits the highest concentration in the range of apogee around 750 km, with perigees ranging from 200 to 500 km (Fig. 2a of Figure 5) (18). This distribution forms a "banana" shape around Earth, with the highest concentration of debris occurring at perigees between 200 and 500 km. The proposed plan involves placing the spacecraft into an elliptical orbit that is coplanar with the debris and at the same eccentricity. This ensures that the collectors' and debris' path meet at perigee. Since the collecting spacecraft will be in a smaller orbit than the debris, it will travel faster, enabling the capture of the debris. This process will be repeated by adjusting the spacecraft orbit to match that of the target debris, allowing for the capture of all debris in high-concentration orbits.

A single spacecraft is insufficient to capture all debris. Given that the debris' apogee spans approximately 750 km

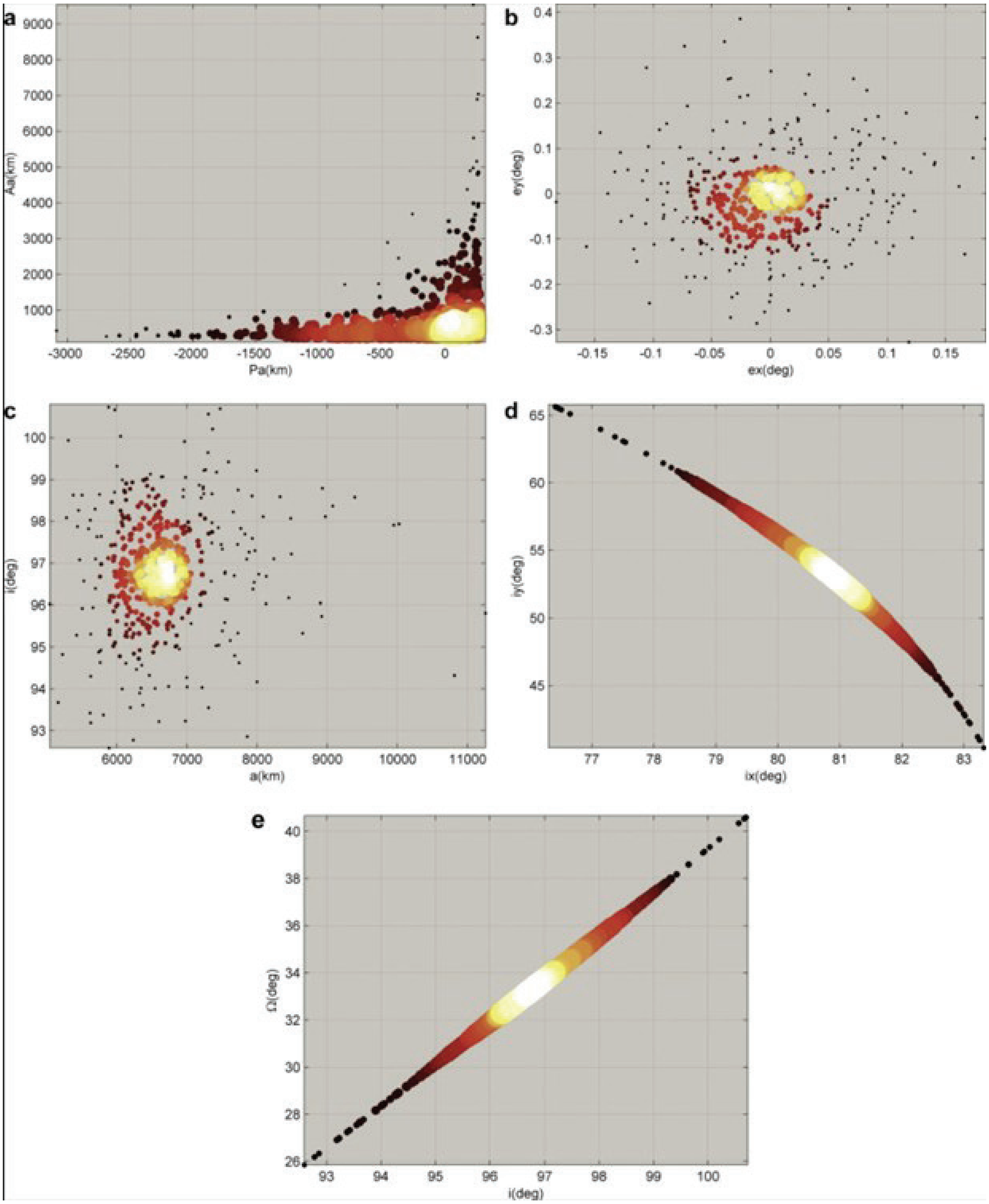

Figure 5. Secondary debris in the plane of orbital parameters. a) altitude of perigee and altitude of the apogee. The Earth radius used here is 6371 km. b) eccentricity vector. c) semi-major axis and inclination. d) inclination vector (18).

and the perigee ranges from 200 to 500 km, clearing even a single kilometer of debris would require 200 orbits. For a 300 km stretch, this would amount to 60,000 orbits, taking over 10 years to complete. For this reason, the proposal is to deploy 10 individual spacecraft, each in orbits with different perigees that match that of the debris', spaced 30 km apart: [230, 260, 290, 320, …530]. Additionally, these spacecrafts will be phased by 33º. While the perigee of each spacecraft will match the perigee of some orbiting debris, the semi-major axis of the spacecraft will be larger than the debris. This will ensure that the spacecraft travels faster than the debris at a given perigee and can capture the debris particles. After each orbit through the debris field, each spacecraft will fire its thrusters to increase its perigee by 5.4 meters, the width of the collection system.

While it is difficult to determine the collision frequency of the collectors with the target debris, NASA's Space Detection System was aimed at determining the orbital debris flux for particles ranging from 50 micrometers to 0.1 meters. Based on the model for 2016, at an altitude of 400 km, it would be expected that the collectors would encounter 1,000 - 0.2 m^2 of particles ranging from 10 - 1,000 micrometers in diameter (Figure 6) (19).

As the spacecraft impacts the debris, the collisions will slow it down, causing a slight decay in orbit over time. This will require less fuel and maneuvering to drift down to the next orbital level compared to boosting the spacecraft to a higher orbit. Starting in a higher orbit, under ideal conditions, the spacecraft will take exactly 5,556 revolutions to clear 30 km of debris. With 16 orbits per day, it will take approximately 347.25 days—just under a year—to clear this distance. Once all orbits are completed, the collection system will retract back to its launch position. To decelerate the spacecraft, the spacecraft will fire its retrograde rockets and uncontrollably re-enter Earth's atmosphere, splashing down in the ocean.

Operations

Rocket Lab's reusable Electron launch system is well-suited for this mission, offering the necessary capabilities to deliver the spacecraft to LEO. The Electron has a payload capacity of 300 kg to LEO, which aligns with the estimated weight of the spacecraft. While the payload fairing is cone-shaped and imposes dimensional constraints, Rocket Lab offers an expanded fairing nose cone that can easily accommodate the spacecraft's design (Figure 7) (20).

Once deployed in LEO, the spacecraft will maneuver into the orbit where the collision or ASAT event occurred using small thruster rockets. After maneuvering into the correct orbit, the protective hatch collapses inward to reveal the collection system. At this point, the collection system unfolds and begins capturing the debris.

COSTS OF AEROGELS

The cost to produce approximately one cubic centimeter of aerogel is $1 (21). To calculate the total cost

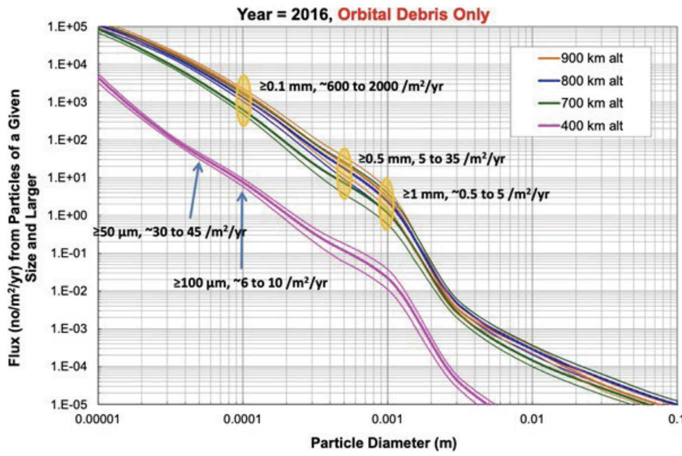

Figure 6. The orbital debris flux predictions at different altitudes. The calculations are based on the NASA ORDEM 3.0 model for the year 2016. The bold curves are the predicted fluxes and the thin curves are the one-sigma standard deviation uncertainties (19).

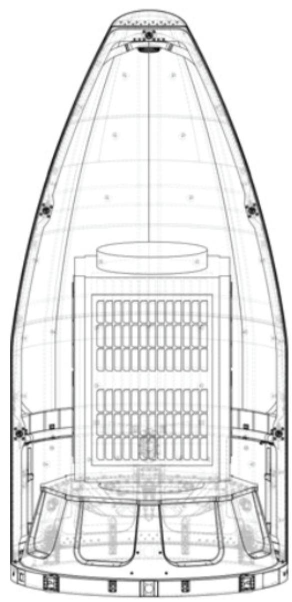

Figure 7. Electron fairing cone with one microsat inside (20).

of the aerogel, the total volume of the cylinder must be found using the equation $\pi r^2 h$, where the radius is 225 cm and the height (or in this case, depth) is 3 cm. This gives a raw volume of 477,129 cm^3. Therefore, using the rough cost of $1 per cubic centimeter, the potential future cost for the aerogel collector itself is around $477,129.

While this may seem like a steep cost, it is nothing compared to the potential cost of the damage that may be caused to satellites or even the ISS from flying space debris. According to Guo, the future anticipated cost of aerogels is $7.2 per cubic meter (22). This could mean that the cost of the aerogel collector could be lowered from $477,129 to only $114.

CONCLUSION

In conclusion, aerogels present a promising solution to the growing issue of space debris. Their unique microporous structure, coupled with their successful application in the Stardust mission, makes them an ideal material for capturing target-sized debris. The spacecraft has been designed to be compact and lightweight, reducing the need for an extensive transport system and consequently lowering launch costs. The staggered orbit configuration enhances the efficiency of debris collection while minimizing the time the satellites spend in orbit. As the cost of aerogels continues to decrease, coupled with the increasing threat of satellite collisions and humanity's aspirations for manned exploration beyond the Moon, these satellites could play a crucial role in safeguarding the future of space exploration.

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DECLARATION OF INTERESTS

The author(s) declare that there are no conflicts of interest regarding the publication of this article.

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