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*Review*

# Thermal life of space Elevators

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**Since the introduction of space elevators by Tsiolkovsky in 1895, many researchers, engineers, and designers stepped forward to suggest theories for the construction of space elevators. Based on the investigations made by many authors for building space elevators, Earth-to-space, Lunar space, and Mars-to-space elevators can contribute for future space exploration and colonization. In the presented study, the aim is to review the previous studies regarding the design and construction of space elevators with appropriate materials and to predict the thermal fatigue life of space elevators for the first time as it is one of the concerns in space environment because space elevators are exposed to thermal cycles. For this purpose, Extended Convex Curves Method is used. The results have shown that the thermal fatigue life of lunar space elevator is less than that for Earth-to-space and Mars-to-space elevators due to the lack of atmosphere on the Moon. This contribution can help to design and construct the space elevators with higher safety against the thermal fatigue failure with the selection of appropriate materials for the space elevator structure.**

**Key words:** Space elevators; thermal fatigue life, thermal cycles, materials, space exploration, colonization.

## INTRODUCTION

### Thermal life of carbon structures

In the previous studies (Anvari, 2017a,b,c, 2018), thermal fatigue life of Unidirectional Carbon Fiber/Epoxy Composite (UD CF/EP) in Low Earth Orbit (LEO), Mars, and Titan environments was investigated. Furthermore, it was mentioned that using Bidirectional Carbon Fiber/Epoxy Composite (BD CF/EP) for the construction of space structures is not recommended due to the reason that according to previous study (Anvari, 2017a,b,c,), crack growth rate in BD CF/EP due to temperature variation is approximately 170 times of that in UD CF/EP. As a result, using BD CF/EP in space structures contains with the high risk of thermal failure. On the other hand, using Carbon Nanotube (CNT) wire in space elevator is recommended (Anvari, 2017a,b,c, because CNT wire is capable to withstand the thermal cycles about 10% higher than that for UD CF/EP. Thus, space structures contained with CNT wire exposed to thermal cycles can last about 10% more thermal cycle numbers to failure when compared to UD CF/EP. Additionally, many other studies also have estimated the effect of thermal fatigue cycles on mechanical properties of different materials (Park et al., 2012; Shin et al., 2000, Giannadakis and Varna, 2009).

In this study, thermal life of carbon structures represents generally the number of thermal cycles that UD CF/EP can last in planets orbits and in space

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environment. The reason is due to the fact that thermal cycles in planets orbits such as LEO, Mars, and Moon's surface have different numerical values. Furthermore, this consideration seems enough because space elevators in this research are exposed to only these thermal environments.

## Space elevators

For the construction of a space elevator, advanced materials are required. One of the reasons is the height of space elevator that can be up to thousands of kilometers. One of the materials that can be used to build the space elevator is CNT because its strength is 100 times of steel while its weight is less than the steel. However, other materials such as boron/epoxy and graphite epoxy can also be used (Smitherman, 2000).

Application of pressurized Shell can be employed to strengthen the compressive tolerance of the space elevator. For obtaining high-speed in space elevator, application of magnetic propulsion is recommended (Smitherman, 2000).

Construction, operation, and deployment of space elevator accompanied by engineering designs and computer simulation have been investigated by many authors. The timeline which is estimated to construct the space elevator is during the next decades. One of the exact predictions for building the space elevator is in 15 years which may allow to make a low-cost space elevator from Earth to space transition. For the construction of Moon or Mars to space elevators, a few considerations for low-gravity ambient, and lunar or Martian surface adaptation are required to be considered (Edwards, 2003).

The idea of space elevator was introduced by Tsiolkovsky in 1895 for the first time. According to his opinion, for constructing the space elevator, application of advanced materials is required to be considered (Eubanks, 2012).

For enhancing the era of space exploration; robotics, artificial intelligence, and nanotechnology can make significant contribution. Furthermore, human body biological modification via drugs may allow the astronauts to live in the harsh environment of outer space. Additionally, with performing a lot of research on carbon materials, the idea of space elevators by construction with carbon structures appeared to be possible. Consequently, a detailed design with carbon structure has been suggested (McCray, 2012).

Access to space is difficult due to the infrequent launches, high cost, and pollutants. Space elevator which is a long cable from the Earth to space can be the key to solve these issues. Moreover, space elevator can decrease the environmental concern and eliminate the falling back of engines back to Earth caused by launches. Epoxy seems to be durable with high strength material which can form a composite with fibers to be included in space elevator. According to the current research, the best location to set up the Earth-to-space elevator is 2,500 km in west of Ecuador, but on equator. Aluminum, gold, and platinum are the materials which can be used to coat the space elevator against the space environment. Nevertheless, it appears that aluminum can be the best option due to its lightweight and non-reactivity. Additionally, aluminum creates a good shielding against the radiation. Based on the theories, first space elevator can be applied to build other larger and complex space elevators. Space elevators will contribute to future faster asteroid mining, colonization, and space exploration (Hontz et al., 2016).

According to the recent research, improvement in tether material is required to build a space elevator. Furthermore, lunar space elevator could be constructed with recent technology by applying tether polymers. For building space elevators, methods should be considered to lower the cost, shorten the time, enhancing human explorers, and robotics. Best methods can be considered the methods with minimum transportation costs versus launch, in a faster timeframe (Eubanks and Radley, 2016).

Space elevator is defined as a cable which is attached at one end to the planet and the other end is floating in space with the length of about 60,000 miles. Based on the recent materials research for space elevator, CNTs is one of the candidates which can be used to build the structure of space elevator due to its high tensile strength equal to 130 GPa and lower weight when compared to steel and Kevlar, and low taper ratio (Edwards, 2016).

One of the keys for cost saving in construction of lunar space elevator is to use lunar materials. There are several issues that need to be considered and controlled prior building the space elevator such as its length and vibration. For building the Mars-to-space elevator, Mars' dust storms and avoid impacting to Moons of the Mars are also needed to be considered, seriously. Earth-to-space elevators can be used to colonize Mars in the future. Based on the calculations, in constructing the lunar space elevator, composite materials with lower tensile strength than CNT can be used (Raitt, 2017).

LiftPort Company and Obayashi organization in Japan are expecting to build lunar space elevator on Moon and construct Earth-to-space elevator by the end of 2020 and 2050, respectively. In 1972, James Cline proposed a Moon cable to NASA for using as space transportation. In 1977, Hans mentioned several materials which can be used to build the Mars-to-space and lunar space elevators such as graphite, silica, fiberglass, steel, and Kevlar. Later in 2003, Weinstein suggested creating a civilization on Mars by constructing the Mars-to-space elevator. Additionally, in 2011, Eubanks and Laine proposed a mission to construct a lunar space elevator with the length of 264,000 km with current technology (Raitt, 2017).

According to the researches, deploying space elevators have many benefits such as solve crisis in energy, reducing greenhouse gas, space access, recycling of high entropy and toxic materials, store water in orbit for upcoming manned missions, secure and safe delivery, colonization of Mars, Moon, and asteroids, and developing room to grow (Raitt, 2017).

Furthermore, for construction, research, and consideration of special issues related to deploying space elevator, “Obayashi Corporation’s space elevator construction concept” is submitted by Ishikawa (2016), “space elevator technology and research” is investigated by Knapman (2016), and “Introduction to this special issue on space elevators” is provided by Raitt (Raitt, 2016).

It appears that many investigations have been performed to design and construction of the space elevators on Earth, Mars, and Moon. Nevertheless, it seems that there is no research related to the prediction of thermal fatigue life of space elevators in their environments. Estimation of thermal fatigue life of space elevators are of high significance because space elevators are subjected to high thermal cycles in planets orbits and space while rotating around the planets.

Consequently, in this study, the goal is to predict the thermal fatigue life of space elevators in planets orbit and space. The results of this research can contribute to prevent thermal fatigue failure by choosing appropriate and adequate coating to shield the space elevator against the thermal fatigue failure in different planets orbit and space.

## CARBON STRUCTURES

“Advanced carbon fiber-reinforced composite laminates have been widely used in satellite structures, where the advantages of these materials-their high specific stiffness, near-zero coefficients of thermal expansion (CTE) and dimensional stabilities make them uniquely suited for applications in a low-specific-weight environment. However, since the beginning of composite structure applications, there has been a strong need to quantify the environmental effects on the composite materials based on the coupon-level laminate test data. Recent studies have shown that the environmental conditions that are the most representative of space and that tend to degrade the properties of composite laminates involve vacuum, thermal cycling atomic oxygen (AO) and micrometeoroid particles. In this respect, there is significant interest in the construction of an experimental database to capture the collective understanding of the degradation mechanisms of composite laminate in in-service environments. It is necessary to be able to predict the long-term durability of composite laminates with engineering accuracy to use these materials with confidence in critical load-bearing structures” (Park et al., 2012). The cross-section (Anvari, 2017a,b,c,) and material properties (Park et al., 2012; Karadeniz and Kumlutas, 2007) of UD CF/EP is illustrated and indicated in Figure 1 and Table 1, respectively. Additionally, the cross-section dimensions and arrangement of UD CF/EP is shown in Figure 1a and b, respectively. It is important to notice that in Figure 1 the diameter of carbon fibers’ bundle embedded in epoxy is 0.5 mm. According to this cross-section (Anvari, 2017a,b,c,), the volume fraction of carbon fiber used in UD CF/EP is 19.6%. As a result, the volume fraction of epoxy in UD CF/EP is equal to 80.4%.

## THERMAL CYCLES TO FAILURE PREDICTION

In this part of the manuscript, the method to predict the thermal fatigue life of UD CF/EP which may be used in the space elevator structure is explained. For this purpose, Extended Convex Curves Method (ECCM) can be applied which has been introduced in 2018 (Anvari, 2018). Furthermore, the estimation results from ECCM can be used to predict the thermal fatigue life of CNT wire as well. The reason is based on the research which has been performed in 2017 (Anvari, 2017a,b,c,), thermal fatigue life of CNT wire is about 10% higher than UD CF/EP.

In this study, thermal fatigue life of UD CF/EP is estimated in space, Moon, Mars, and Low Earth Orbit (LEO) environments. Since Moon does not have any atmosphere (Pasachoff, 1993), in this study, the thermal cycles to failure for UD CF/EP in space and Moon can be considered as the same value. Because in Moon and space in solar eclipse and sun illumination the temperature may be assumed to be -196 and 125°C (Zimcik et al., 1991), respectively.

The space elevator attached to any planet such as Earth, Moon, and Mars will rotate with the planet. Hence, it will go through the solar eclipse and sun illumination. The Earth-to-space elevator will experience approximately two kinds of thermal cycles. The first is in LEO in lower altitudes and the second at high altitudes in space. In LEO, the thermal cycle varies from -175 to 120°C (Park et al., 2012), while in space, the thermal cycle varies from -196 to 125°C (Zimcik et al., 1991).

On the other hand, it seems that lunar space elevator experiences the same thermal cycle in all altitudes which is -196 to 125°C (Zimcik et al., 1991). The temperature variation on Mars varies from -123 to about -73°C (Pasachoff, 1993) in worst environmental conditions in Mars’ winters that the temperature is extremely cold. Nevertheless, the Mars-to-space elevator at high altitudes in space where there is no atmosphere experiences -196 to 125°C (Zimcik et al., 1991) in each Mars rotation from solar eclipse to sun illumination, respectively.

In the presented section of the manuscript, thermal fatigue life prediction of UD CF/EP in space is explained

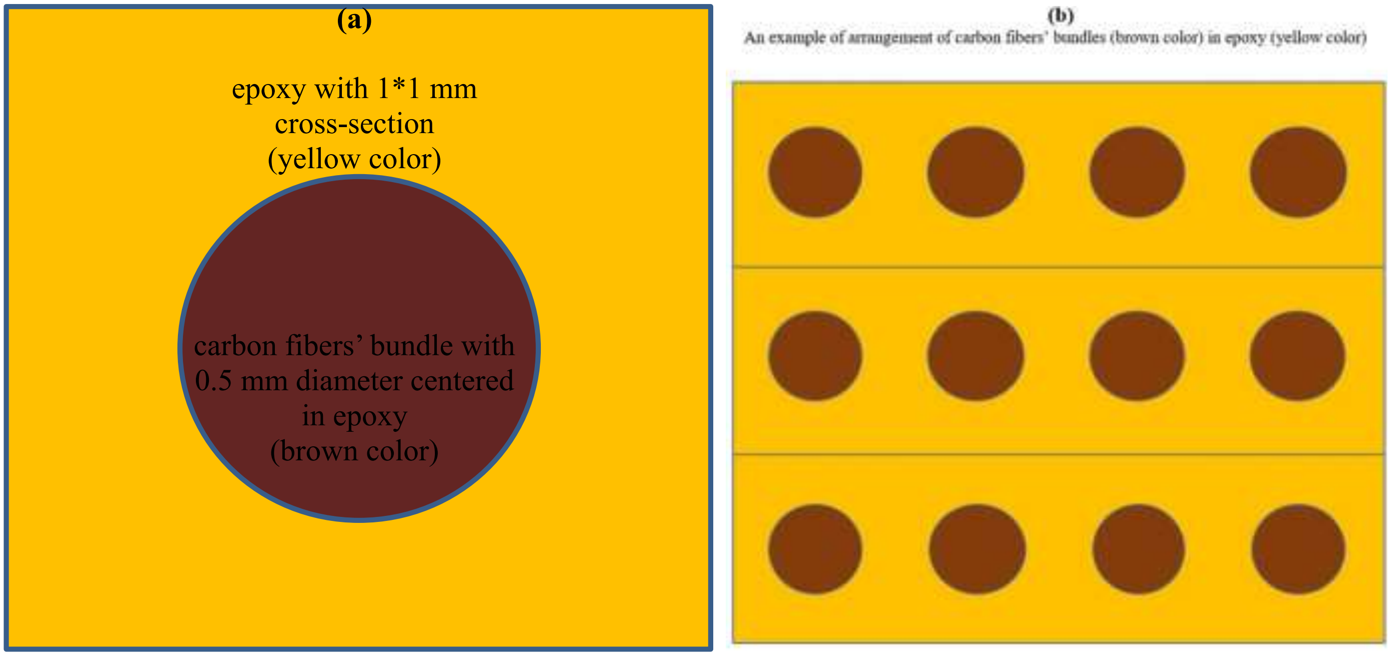

**Figure 1.** Cross-section of the UD CF/EP (1); dimensions (a) and arrangement (b), from up to down, respectively.

as an example. Hence, this procedure is repeated to derive the thermal fatigue life of UD CF/EP in LEO and Mars as well. For deriving the thermal fatigue life, Equation 1 (Anvari, 2018) can be used.

$$\mathrm{ILSs}_{\max} = \mathrm{ILSS} \quad (1)$$

This Equation is the equalization of the maximum Inter Laminar Shear stress ($\mathrm{ILSs}_{\max}$) with Inter Laminar Shear Strength (ILSS) for UD CF/EP. It means that when $\mathrm{ILSs}_{\max}$ reaches ILSS, it is the end of thermal life of UD CF/EP which can be applied in space elevator structure. Of course, this failure contains with crack propagation and fracture of the structure. For calculating Equation 1, Equation 2 (Anvari, 2018) can be used as it is the extension of Equation 1:

$$\Delta\alpha.\Delta T_{\max}.G_{\max} = (-4.87\mathrm{e}{-6})\,(\Delta T_{cycle}.N/\Delta T_{LEO})^2 + (3.84\mathrm{e}{-3})\,(\Delta T_{cycle}.N/\Delta T_{LEO}) + 80.9. \quad (2)$$

In Equation (2), $\Delta\alpha$ is the difference of axial coefficients of thermal expansion between epoxy and carbon fiber which is equal to $\alpha_{epoxy} - \alpha_{carbon\ fiber}$. $\Delta T_{max}$ is the maximum temperature difference between the stress-free temperature (23°C) (Park et al., 2012) and environment temperature. $G_{max}$ is the axial shear modulus of carbon fiber. $\Delta T_{LEO}$ is the temperature variation at each thermal cycle in LEO which is equal to -175°C in solar eclipse to 120°C in sun illumination and back to -175°C. $\Delta T_{cycle}$ is the temperature variation at each thermal cycle in the environment which is under study.

As an instance, if the goal is to determine the thermal cycles to failure in space, $\Delta T_{cycle}$ is equal to -196 to 125°C and back to -196°C which is equal to 642°C. Finally, $N$ is the number of thermal cycles to failure in the environment which is under consideration. $\Delta T_{max}$ in the left side of Equation 2 is equal to 23-(-196) which is equal to 219°C which is the highest temperature difference between stress-free temperature and space temperature. With substituting all these values in Equation 2 and 3 it can be obtained to solve for the number of thermal cycles to failure in space or Moon.

For deriving the number of thermal cycles to failure in space (or Moon), $\Delta T_{cycle}$ is equal to (125-(-196)) * 2 which is equal to 642°C. $\Delta T_{LEO}$ is also equal to (120-(-175)) * 2 which is equal to 590°C. $\Delta\alpha$ ($\alpha_{epoxy} - \alpha_{carbon\ fiber}$) from Table 1 is equal to (43.92-(-0.83)) e-6 (1/°C). Furthermore, $G_{max}$ from Table 1 is equal to 7.59 GPa.

$$74.4 = (-5.77\mathrm{e}{-6})\,(N_{space})^2 + (4.18\mathrm{e}{-3})\,(N_{space}) + 80.9. \quad (3)$$

With solving equation (3), $N_{space}$ or $N_{Moon}$ which is the thermal cycles to failure is equal to 1,483 cycles. It means that space elevator which contains UD CF/EP without coating will fail after rotating 1,483 times around the planet and this thermal failure is only for the part of the space elevator which is exposed to space or Moon environment.

This process for deriving the thermal cycles to failure for Mars and LEO are repeated and thermal cycles to

**Table 1.** Material properties of UD CF/EP (Park et al., 2012; Karadeniz and Kumlutas, 2007).

| Materials | Epoxy | Carbon Fiber |
|---|---|---|
| Axial Coefficient of Thermal Expansion (1/$^o$C) | 43.92e-6 | -0.83e-6 |
| Transverse Coefficient of Thermal Expansion (1/$^o$C) | 43.92e-6 | 6.84e-6 |
| Axial Poisson's ratio | 0.37 | 0.2 |
| Transverse Poisson's ratio | 0.37 | 0.4 |
| Axial Elastic Modulus (GPa) | 4.35 | 377 |
| Transverse Elastic Modulus (GPa) | 4.35 | 6.21 |
| Axial Shear Modulus (GPa) | 1.59 | 7.59 |
| Transverse Shear Modulus (GPa) | 1.59 | 2.21 |
| Volume Fraction (%) | 80.4 | 19.6 |

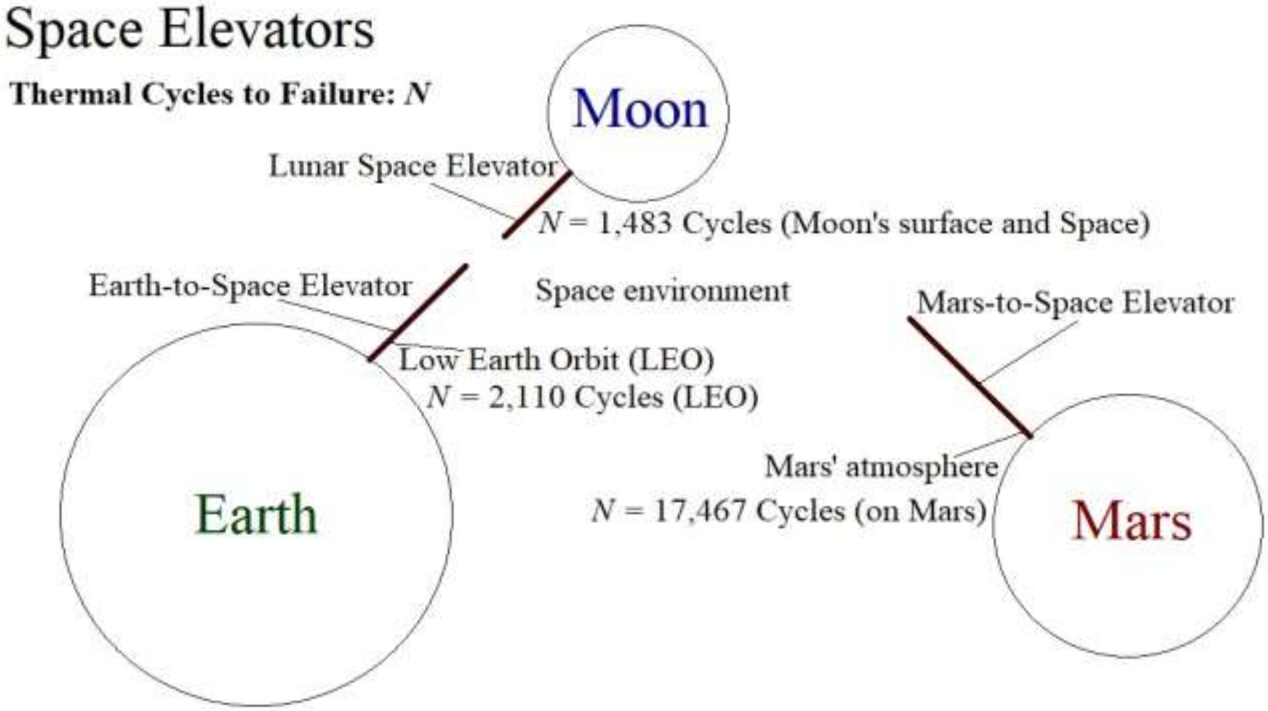

**Figure 2.** Schematic of Earth-to-space, Lunar space, and Mars-to-space Elevators with thermal cycles to failure derived for LEO, Mars' atmosphere, and Moon or Space.

failure are 17,467 and 2,110, respectively. In Figure 2, thermal cycle numbers to failure for Earth-to-space, lunar space, and Mars-to-space elevators at low altitude and in space environments are indicated. As it is illustrated in Figure 2, Earth-to-space elevator has two thermal fatigue lives which one of them is related to LEO environment at lower altitude and the other is related to space environment at higher altitudes.

Furthermore, Mars-to-space elevator also has two thermal fatigue lives. One of them is related to the part of the space elevator at the surface of the Mars in contact with Mars' atmosphere, and the other is related to higher altitudes out of the Mars' atmosphere in space with the values of 17,467 and 1,483 cycles, respectively. On the other hand, because Moon does not have any atmosphere, the lunar space elevator only has one thermal fatigue life which is equal to thermal fatigue life in space environment equal to 1,483 thermal cycles. In all cases, thermal failure includes crack propagation and fracture in the structure which contains UD CF/EP.

## CONCLUSIONS

Thermal fatigue lives of Earth-to-space, Mars-to-space, and lunar space elevators which are built with UD CF/EP have been predicted with ECCM. According to the results obtained in 2017 (Anvari, 2017), thermal fatigue life of CNT wire is approximately 10% higher than UD CF/EP. Hence, by 10% increment in thermal fatigue life of space elevators in this study, the thermal fatigue life of space elevators contained with CNT wire can be derived.

The results of this research indicate that lunar space elevator which is exposed to space environment will have the lowest thermal life which is due to the high thermal cycle in space. On the other hand, the part of the Mars-to-space elevator which is close to the Mars surface in Mars' atmosphere has the highest thermal life which is due to the lowest thermal cycle in Mars environment. Additionally, the thermal cycles to failure in LEO environment is between of that for Mars and space environments.

These results can contribute to calculate enough amount of coatings such as aluminum, platinum, and gold to prevent thermal failure of the space elevators structures in different environments such as Mars, LEO, and Moon or space. As it seems obvious, in different environments, the lower the thermal fatigue life is, the higher amount of coating is required to extend the thermal fatigue life. Since, the calculations of required coating for space elevators is out of the scope of this research, as a result, it can be an appropriate subject of study for the future work.

**Abbreviations: ILSS,** Inter-Laminar Shear Strength; **ILSS0,** Inter-Laminar Shear Strength at zero thermal cycles (maximum ILSS for UD CF/EP); **ILSsmax,** Maximum Inter-Laminar Shear stress; **Δα,** Difference of Axial Coefficients of Thermal Expansion between Carbon Fiber and Epoxy; **ΔTmax,** Maximum Temperature Variation between Stress-Free Temperature and Ambient Temperature in UD CF/EP; **Gmax,** Maximum Shear Modulus in Axial Direction (Carbon Fiber's Axial Shear Modulus); **α carbon fiber,** Carbon Fiber's Axial Coefficient of Thermal Expansion; **αepoxy,** Epoxy's Axial Coefficient of Thermal Expansion; N, Cycle Numbers to Failure in Specific Environment; **ΔT,** Temperature Variation; **ΔTLEO,** Temperature Variation in each Thermal Cycle in Low Earth Orbit; **ΔTcycle,** Temperature Variation in each Thermal Cycle in Specific Environment.

## CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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