Theoretical studies on space debris recycling and energy conversion system in International space station

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Abstract

The space debris management and alleviation in the microgravity environment is a dynamic research theme of contemporary interest. Herein, we provide a theoretical proof of the concept of a lucrative energy conversion system that is capable for changing the space debris into useful powders in the international space station (ISS) for various bids. A specially designed broom is adapted to collect the space debris of various sizes. An optical sorting method is proposed for the debris segregation in the ISS by creating an artificial gravitational field using frame-dragging or gravitomagnetism. An induction furnace is facilitated for converting the segregated metal-scrap into liquid metal. A fuel-cell aided water atomization method is proposed for transforming the liquid debris into metal powder. The high-energetic metal powders obtained from the space debris could be employed for producing propellants for useful aerospace applications, and the silicon powder obtained could be used for making soil for fostering the pharmaceutical-flora in the space lab in the future aiming for the scarce-drug discoveries for high-endurance health care management. The proposed energy conversion system is a possible alternative for the space debris extenuation, and its real applications in orbiting laboratories through the international collaboration for the benefits to humanity.

Introduction

The International Space Station (ISS) is an exclusive scientific podium and an orbiting laboratory that has facilitated interdisciplinary researchers in 106 countries to conduct various *in vitro* trials in microgravity. Although each ISS partner has diverse scientific objectives, the aggregate aim is to encompass the experience and knowledge garnered to benefit all humankind [1, 2]. This is predominantly factual for nurturing medicinal plants in ISS for scarce-drug discoveries for the benefits of humanity [3]. This article is a part of the scientific odyssey that resulted from a collaboration among members from various research groups from physical, chemical, material and biological sciences. Literature review reveals that through fundamental research and development a few products and services derived from space station activities are entering the souk and furthering healthy and peaceful life on Earth [1], which is motivating us to propose more challenging research in ISS. It is evident from the executive summary of ISS, which encapsulates the achievements of innovative research on the orbiting laboratory that had created a positive impact on the quality of life on Earth and the future scope of the interdisciplinary researches globally for creating an impact on scientific advancement [1-16]. Herein we conduct theoretical studies for providing the proof of the concept of space debris recycling and energy conversion system in a microgravity environment with an intention to carry out real-time experiments in the space platform through the multi-national collaboration with wide scope and benefits to humanity.

The growing utilization of outer space for the advancement of the standard of living and hunt for wisdom has led to the accretion of space debris or space junk in high-density satellites orbits. Various reports and industrial engineering data on the usefulness of the prevailing debris extenuation methods are inadequate for a realistic conclusion [4-16]. J.-C. Liou et al. [4-8] reported that as the space debris volume remains to rise over time due to the global space activities in recent years, there is a need to update the debris alleviation normal exercises to stimulate competent and active practices to better abate the risks from space debris for the benign manoeuvres of future space missions. Literature review reveals that the frequency variations of orbital launches are due to the in-house reasons in the participating countries [17]. The current trend of rocket launches globally shows that in the next few decades' large volumes of space debris will be in orbit, which will create a serious threat to future missions. It is comprehended by other investigators that albeit all upcoming space launches are called off, the space debris already exist will be tendering threats for numerous decades to come before all of them re-enter earth and burn off [14-17]. Deepaa Anandhi et al., [17] reported the need for an urgent action on the space debris mitigation independently or jointly by the various beneficiary organizations utilizing the orbital space for meeting the future global needs. Though numerous on going debris de-orbiting programs are intact, the engineering data on the usefulness of the prevailing debris extenuation procedures are inadequate for a reliable judgment [18]. Briefly, an enhanced volume of space debris has become a menace to live satellites, ISS and various space missions. Although many studies have been reported over the decades on space debris management and alleviation, the space system designers reported that there are no foolproof techniques for tracking and mitigation of space debris having the object size between 1 cm and 10 cm, which could cause significant damage to live satellites, future space vehicles and the ISS [18]. Although every space agency is persuaded to reduce space debris whenever feasible by using their state-of-the-art modus operandi, there may be some parts that would be liberated and orbiting for obvious causes beyond control. This situation was observed by many space agencies when a physical part of the space vehicle was departed in geostationary transfer orbit (GTO) during a multiple payload mission [10]. Therefore, it is essential, rather enviable, perhaps predestined for inventing lucrative and efficient methods of space debris mitigation. United Nations (UN) Committee on the peaceful uses of outer space reported that the most challenging part of the space operations is the collision avoidance. It also reported that the space debris curing issues certainly entails joint action by all participants [11].

The central idea of the space broom governed by the dual-head electromagnetic (DHEM) device [19], is to mitigate the intermediate size of the space debris object, which could otherwise pierce holes in the structure of the ISS and live satellites, particularly in the low earth orbit. It is estimated that the space debris could crash any space vehicle at a velocity greater than 48,280 km/hr [18]. Hao Jiang et al. [20] carried out tests in microgravity and reported that robotic grippers based on dry adhesion are a workable option for purging space debris in low Earth orbit. The DHEM space broom with variable sweeping speed developed by V.R.Sanal Kumar et al. [19] could be a useful method for the space debris mitigation and its collection for recycling it in the orbiting space lab through the lucrative energy conversion methods. The DHEM space broom could be redesigned for capturing the inactive satellites, rocket fragmentation debris, and other non-functional objects or debris pieces from the low earth orbit. The environmental report (2019) of the European Space Agency (ESA) highlighted that space debris mitigation requires a level playing field to achieve long-term stability. The ESA highlighted in its annual space environment report (2019) that the production of space debris via impacts and blasts in orbit could lead to an exponential growth in the volume of artificial objects in space [21]. Therefore, the menace of space debris to the future of spaceflight, united with the closely world-wide embracing of the U.N convention (1972) on global accountability for damage caused by space objects, created the need for a set of internationally accepted space debris mitigation measures [22]. Recently the ESA emphasized the need of world-wide devotion to invoking space debris alleviation measures lucratively. The accessible global literature reveals that *no one* attempted yet (2020)**,** the recycling technique to change the debris into powders in the ISS for multiple applications [14, 15].

Report (2019) reveals that India contributed around 400 pieces of orbital debris through their anti-satellite missile test (ASAT), which increases the risk of threat to the ISS on the order of 44 % [18]. Since the test was done in a low altitude to restrict the orbital lifespan of ensuing debris, the space agency claimed that whatever debris that is generated would decay and fall back onto the earth within weeks and the ISS will not be at risk, as it is in the higher orbit. However, there are possibilities of the orbital lifting of space debris due to missile impact, which could create threat to the ISS. Therefore, in future such tests must be avoided by all the space agencies or must be done with caution as the ISS is a human inhabitant and an orbiting laboratory, which is to be protected with zero-risk. It is well known that the non-responsive satellites are the high-risk space debris to the operational satellites and the ISS. The primary structure of most of the satellites consists of aluminum, beryllium, stainless steel and titanium. The appendage booms, antenna dishes (made of aluminum / steel), platforms, solar panels (made of silicon / germanium), and support trusses, are common secondary structures. The mounting brackets, cable supports, copper wiring and connector panels, electronic boxes, and silicon made printed circuit board (PCB) are categorized as tertiary structures [23]. Literature review reveals that Aluminum 6061, a potential fuel for solid propellant, is used as the primary structure of the CubeSats [24]. Therefore, any combined method to mitigate and recycle the space debris with an innovative energy conversion method could create a win-win situation, which is attempted herein.

In this paper a cogent conceptual method has been proposed for converting the space debris into lucrative solid fuels in the ISS with artificial gravitational field. Note that M.Tajmar [25] reported two different system designs that could generate an artificial gravitational field using frame-dragging or gravitomagnetism. It is known that frame-dragging is an effect on spacetime, predicted by Albert Einstein's general theory of relativity, which would be used to generate artificial gravitational fields similar to electric fields generated by time-varying or moving magnetic fields with enhanced field strength [25].

The space broom operated by a DHEM device is used for capturing the space debris from the space environment [19]. An optical sorting method will be used in the ISS for segregating the collected debris into individual material and metal scraps. Using an electric channel induction furnace, the separated metal scraps are converted into the molten metal form. Further, a lucrative water atomization system operated with a fuel cell has been adopted for converting the molten metal into powder form, which produce the end products, viz., the metal powder and the water. The segregated selected powders are utilized for making solid propellant for chemical propulsion. The specially separated silicon powders are used for building feigned soil for nurturing*pharmaceutical flora* in the ISS for the *scarce drug*discovery for the high-endurance health care management [3, 26-28]. An inclusive layout of the proposed methodology for space debris mitigation and the energy conversion technique are described in the subsequent section.

METHODOLOGY

The comprehensive layout of the energy conversion system used for changing the space debris into fuel and feigned soil is shown in Fig.1(a-b). The detailed report of an analytical case study, along with the requirements of electricity and water in the ISS for separating aluminum and silicon powder from the space debris, is presented in the subsequent section (see Table-1). The following lucrative steps are proposed for the collection of composite space debris and further its conversion into powder form for various applications in physical, chemical, pharmaceutical and biological sciences.

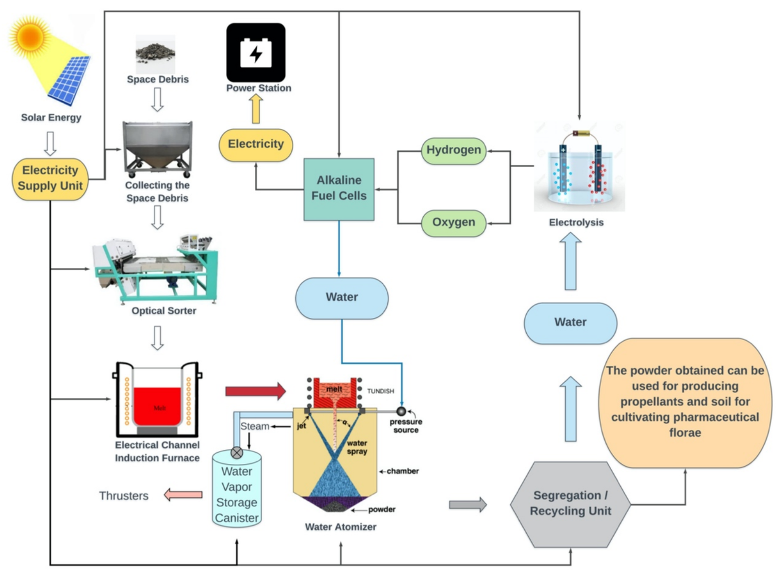

Figure 1(a) The proposed process layout for converting the space debris into powders.

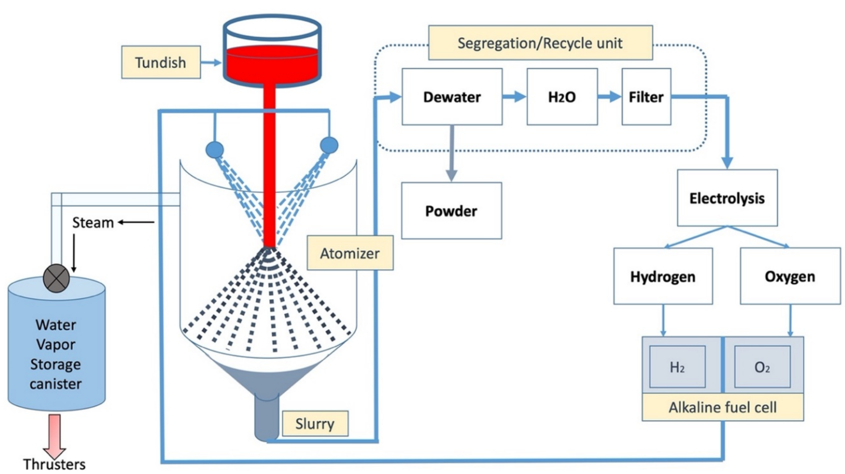

Figure 1(b) The proposed process layout of the water atomization process.

Debris collection method

The DHEM space broom proposed by V.R.Sanal Kumar et al. [19] is chosen as a profitable method for the collection of space debris to the ISS. The feedback controlled variable sweeping speed DHEM space broom will be capable of capturing all the space debris nearing to the ISS including the non-functional objects having an average size between 1 cm and 10 cm, which are moving with different velocities and directions and polluting the space environment and creating risk to live satellites and space vehicles. Note that the debris capturing net made of*Graphene* material, and the bidirectional plasma thruster [29], could be other options for space debris collection for the operational protection redundancy. The technology of the net proposed by ESA [30] in this regard could be used for capturing the debris after decelerating it using plasma thrusters.

Debris sorting method

A mechatronic control device, with cameras and/or lasers, is proposed for separating the irregular-shaped debris into discrete materials, viz., magnesium, aluminum, etc. [31]. The device could achieve to sort out 2000-3000 particles per second, with a minimum power consumption (~1 kW) [32, 33].

Debris melting method

The amount of electrical energy required for the electrical channel induction furnace for melting the collected debris in ISS is estimated onboard using an algorithm with traditional thermodynamics' equations. The evolved gases from the molten debris are collected in separate canisters for the profitable design of the space thrusters for numerous applications onboard and off board, which comprises the desirable orbital tweaks of the ISS. The entire system will be in a capsule facilitated with an artificial gravity generator to create a gravity induced free-falls of fluids. As stated earlier, an artificial gravity could be created using an artificial gravitational field using frame-dragging or gravitomagnetism [25] or by invoking a centripetal force.

The powder fuel production

A well**-** designed *tundish* is equipped in the ISS for storing the liquid paste in the molten state (**see Fig.1(b)).**And for converting the molten material into small granules, a high velocity water jet is facilitated in the atomization process in the*space lab* with multiple nozzles. The small granules could be placed in the alloy powder box after sorting out, and the water will be recycled through the dewatering system and filters. The collected granules are dried and the sizes of the granules are regulated according to onboard applications. A loss of 3-5 % is anticipated during the sieving of powders. The required water for the atomization administration is acquired from the proposed recycling, alkaline fuel cell, and electrolysis methods. The proposed electrolysis method is the alkaline water electrolyzer, which could operate at a low temperature (80^{o} C – 200^{o} C) with an efficiency of 70-80 %. The proposed system is capable to prevent powder oxidation and thermal self-ignition [34]. Note that until recently (2019) water atomization process was not used to creating aluminum and aluminum alloy powders primarily due to the anticipated detonation risk due to the secretion of hydrogen as a result of powder interaction with water. Furthermore, water atomization process was not, recommended due to the apprehension of powder oxidation and the deterioration of powder properties. Admittedly, these problems have been resolved at the Institute for Problems of Materials Science (Kiev, Ukraine). These are succinctly reported by Oleg D. Neikov et.al. [34].

In our system, the heat energy obtained from the electrolysis process is used for drying the powders. The desired powders are separated with an objective for creating feigned soil in the ISS for cultivating pharmaceutical flora. Furthermore, the other selected metal powders are mixed with oxidizers and binders for making solid propellants for chemical propulsion. The powders, essentially aluminum, obtained with the desirable properties of solid propellants could be used for micro-thrusters for nanosatellites or devising other propulsion systems in the space lab. The silicon powder segregated from the debris powder could be used for making artificial soil in the ISS for vegetation as it plays important roles in mineral nutrition of plants. Note that silicon fertilizers today are very common in many crop production systems worldwide as it shows the significant amount of evidence in improving crop productivity [35]. The comprehensive process layout highlighting the water atomization process is shown in **Figure 1(b).** As mentioned earlier, the water atomization process and the other systems will be placed in a capsule where the artificial gravity environment persists. In this study, we are suggesting a water-cooling method for cooling down the system. The steam evolved during the process will be collected in a different water vapour storage canister. The steam will be regulated in the gaseous phase and will be used for the selective thrust-vectoring of the space station / ISS. Alternatively, steam evolved during the process can also be recycled and used as water resources for the atomization process. The temperature inside the capsule is maintained using the ATCS (Active Thermal Control System) which is currently used in the ISS to regulate the temperature [36]. However, a further experimental study on water atomization and the cooling system in a microgravity environment is required for its qualification.

AN ANALYTICAL CASE STUDY

In our case study 1 kg of aluminum powder is selected for conversion into useful fuel onboard. It is evident from **Figure 2** that aluminum alloys are the major constituent of the space debris [37], which often collide with the ISS. Note that using the recommended technique (see **Figure1(a-b)**), we estimated that, about 97 % of aluminum powder could be acquired from the hoarded aluminum debris. A loss of 3-5 % is anticipated after the water atomization process because of the sieving.

Note that by varying the water jet speed we could achieve the desired size of the powder. Granules' size can be adjusted by either the water jet pressure or the nozzle size adjustment in which the molten liquid is poured [34, 38]. Water jet pressure can be controlled either by the nozzle jet size or water flow rate.

The process layout is depicted in **Figure 1(a-b)** . The required amount of electric power, water, heat**,** and the scale of pressure for converting the 1 kg of aluminum debris into fuel are highlighted in **Table-1** . In order to process 1 kg of debris in a visual separator, an amount of 1.85 milliwatts power is required at an operating temperature of 40° C at a pressure of 700 kPa.

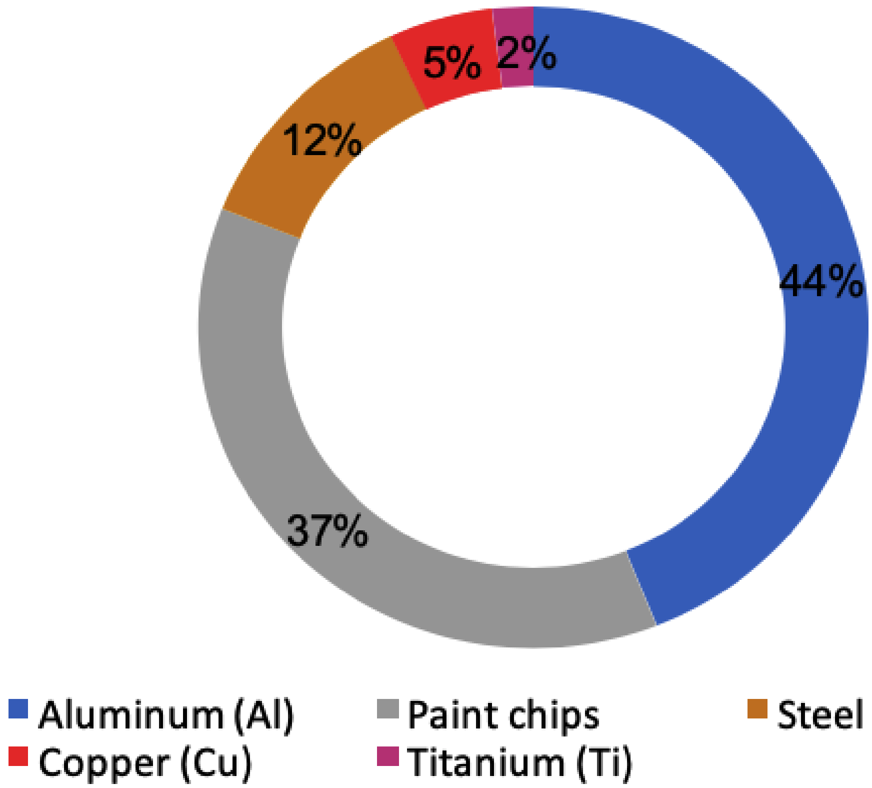

Figure 2: A circle graph is demonstrating the percentage of materials that frequently blow on ISS.

Table 1 Power and Water Requirements for Transforming 1kg of Aluminum into Fuel [18]

Process	**Electricity (W) (Power)**	**Water**	**Temperature (**
Segregation	0.00185*	-	40
Liquefaction	273.33**	-	750 **
Liquid alloy to powder conversion	3000-5000**	12 liters/kg**	750-1000
Recycling unit (Filter and Dewater)	18000 (1500 W/liter of water)	Recycling of the generated water	24 for filter & 55
Electrolysis	50000***		60-80
Bacon fuel cell	33330	9 liters/kg***	90

** for administering of 1kg scarp in the space lab** for administering of 1kg aluminum*** Hydrogen***Table 2** The components and the connected materials used in the SNUSAT

Elements	**Constituents**	**Mass per unit (kg)**	**Amount (Nos.)**	**Allow**
Sun Sensor	Al, Si, Cu	0.005	3	5
Earth Sensor	Al, FR-4, Cu	0.050	4	10
Star tracker	Baffle material, Carbon nanotube coating, Cu	0.050	1	10
GPS	Al, FR-4, Cu, Si	0.050	1	5
Reaction wheel	Stainless steel	0.045	3	5
EPS board	Polystyrene	0.105	1	5

Elements	Constituents	Mass per unit (kg)	Amount (Nos.)	Allow
Batteries	Lithium-Polymer, FR-4	0.256	1	5
Solar Panel	Ge	0.100	4	10
UHF Transceiver	Al, FR-4, Si	0.075	1	5
S-band transmitter	FR-4, Cu	0.062	1	5
S-band antenna	Steel	0.100	1	5
UHF antenna	Al, FR-4, Cu	0.100	1	5
Structure	Al	0.500	1	10
On board Computers'	Al, Cu, Si, FR-4	0.055	1	5
EPOIS	Camera Material	1.000	1	10
Thrusters	Al, propellants	0.500	1	10
TOTAL		**3.063**		

Source: APCL, Aerospace Engineering, SNU, Seoul, The Republic of Korea*(Al – Aluminum, Cu - Copper, Ge – Germanium, Si – Silicon)* An amount of 273.33 W electric energy is required for melting 1 kg of aluminum in the ISS at a temperature of 750° C and pressure of 96.52 kPa. Additionally, 750-1000° C range heating system is required to retain aluminum in the liquid state at a pressure of 1.03 MPa in the atomization process of 12 liters of water, obtained from the alkaline fuel cell, at an electric energy consumption of 3-5 kW. The potassium hydroxide is used as an electrolyte in the alkaline fuel cells at a temperature of 90° C at a pressure of 101.35 kPa. During this process 9 liters of water and 33.33 kW of electricity are acquired as derivatives for 1 kg of hydrogen. The required amount of water is generated from the *Bacon fuel cell* for the atomization process. The estimated electric power needed for atomization, dewatering and filtering processes is 1.5 kW. Note that a temperature of 55° C for dewatering [39] and 24° C for filtering must be maintained in the system. The water is segregated into hydrogen and oxygen with the aid of the potassium hydroxide as an electrolyte at an energy consumption of 50 kW for 1 kg of hydrogen at a temperature range of 60-80° C, and at a pressure of 3 MPa. The generated hydrogen and oxygen are permitted to recycle in the onboard system to produce the water continuously for the water atomization process. The required powder, as an end product with desirable size, is obtained through appropriate sieving. Note that, if necessary, hydrogen gas could be either transported from the earth or obtained from space by utilizing the Bussard's ramjet [40].

The solar energy conversion system is invoked for an efficient power generation, as the ISS has 2,500 m^2 solar panel, which could produce up to 84–120 kW [41]. Additionally, the fuel cell could contribute 33.33 kW of electricity, which mainly utilized for the recycling process. In the proposed technique, a total amount of 40 kW is required for processing 1 kg of aluminum. It is estimated that up to 1 kW power can be generated using a solar panel with one square meter area.

The satellite, named SNUSAT-2, a 3 U CubeSat designed and developed by the Seoul National University (SNU), South Korea for remote sensing is selected for our analytical case study. The main elements and the connected materials employed in the SNUSAT are given in**Table-2** . It is evident from the component details that once this SNUSAT becomes non-operational**,** it gives 1350 g of aluminum powder. In the case of a non-operational Vanguard-1 [42] we could collect an amount of 1420 g of aluminum through recycling, which could be converted into fuels for spacecraft propulsion.

CONCLUDING REMARKS

A theoretical proof of the concept complemented with the pragmatic methodological approach has been established herein for converting space debris lucratively into fuels and also for building soil from silicon powder for fostering the *pharmaceutical flora* in the space lab of ISS for the drug discoveries. During the recycling process at the artificial gravity condition, the evolved gases could be stored in the canisters for devising thrusters for various aerospace propulsion applications. Note that, using these thrusters, the ISS could be shifted to the subsequent orbit after mitigating all space debris from the nearest surroundings. Briefly, the recycling energy conversion system proposed herein could be utilized for the possible orbital trajectory changes of space labs. Through our analytical estimation we concluded that 1 kg of aluminum debris could produce ~ 0.96-0.98 kg of aluminum powder for producing valuable fuel for chemical propulsion. Additionally, we could conclude that the silicon powder created could be used for producing feigned soil for fostering*pharmaceutical flora* in the ISS to discover scarce-drugs for high-endurance health care management. It leads to say that one can aim for cultivating medicinal plants in the space lab for discovering suitable drugs for enhancing the heat capacity ratio of blood for reducing the risk of *asymptomatic stroke* and *acute heart failure* in the gravity and microgravity conditions presumably due to the variations in blood viscosity and turbulence level in the circulatory systems of human being and animals. These are succinctly reported *in toto* by V.R.Sanal Kumar et al. [3, 26-28]. It is known that cardiovascular risk is higher in astronauts / cosmonaut but the fundamental cause of such risk is still unknown to medical science [3, 43, 44]. Michael D. Del et al. [43] highlighted that Apollo lunar astronauts exhibit higher cardiovascular disease mortality. It is important to note that the world-wide space agencies and nations are contemplating for the extended manned missions to *Mars* and the*Moon* . In such manned missions, health risks could be escalated as travel goes beyond the Earth's protective magnetosphere into the more intense deep space radiation environment. Therefore, suitable drug discovery is inevitable for increasing the thermal tolerance level [3, 28] for reducing the cardiovascular risk of the inhabitants (human being / animal) of the space vehicle or space lab. Clare Wilson [44] reported (2019) that being in microgravity can have strange effects on the body, including people's blood flow backwards. K. Marshall-Goebe [45] reported that exposure to a weightless environment during space flight results in a chronic headward blood and tissue fluid shift compared with the upright posture on Earth, with unknown consequences to cerebral venous out flow. All these findings lead to say that high endurance health care management is required for reducing the risk of cardiovascular disease mortality of astronauts / cosmonaut for conducting experiments in the space labs. Further discussion on the medical application of our study is beyond the scope of this short communication.

Briefly, our theoretical concept study will create a win-win situation through real time experiments in the orbiting space lab by recycling the space debris lucratively, for creating end products for the benefits to humanity. We concluded that the proof of the theoretical concept presented herein could be implemented in real-time in any space lab for the debris mitigation and recycling in accordance with the procedural requirements set for meeting the safety and mission assurance [46-50]. Note that additional materials (fuel/oxidizer) and/or additives must be available on board for making solid propellants for getting desirable specific impulse, as the case may be. Additionally, sufficient water must be produced using on-board fuel-cell for vegetation. These are identified as minor limitations in making the desirable end product without any prerequisite. Nevertheless, barring all limitations, we concluded that the space debris-recycling and the energy conversion system described methodologically herein are viable options for producing the end products in the ISS for various biological and aerospace applications in the future for the benefits to humanity.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Amrith Mariappan contributed to the conceptualization, theoretical analysis and writing the original draft and layouts. V.R.S.Kumar supervised the work and extended the concept aimed in biological and aerospace applications and edited the final manuscript. Steve Weddell assisted the first author for drafting the manuscript and provided the intellectual input. Vishnu Anand and In-Seuck Jeung provided the SNU CubeSat design details for theoretical analysis with intellectual input for conclusion and AIAA presentation.

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