ACS OMEGA

http://pubs.acs.org/journal/acsodf

Review

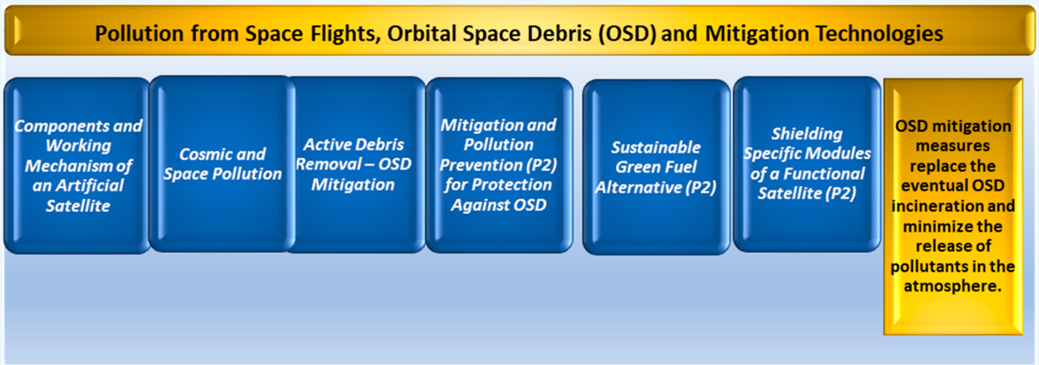
Pollution Effects and Management of Orbital Space Debris

Zarook Shareefdeen* and Hadeel Al-Najjar

Cite This: *ACS Omega* 2024, 9, 5127–5141

Read Online

ACCESS | Metrics & More | Article Recommendations



ABSTRACT: In recent years, spacecraft launches have increased significantly, leading to an increased risk of orbital space debris (OSD) collision, translating into further growth in OSD. With the recent space legislation reducing satellites' end of life period in orbit from 25 to 5 years and with the current OSD amounting currently to nearly 130 million pieces, there emerges the imperative need to reduce and manage OSD significantly. Even without the potential future launches, tracked OSD by itself is alarming and requires intervention and abrupt mitigation. This Review highlights the type of pollutants, including spacecraft combustion pollution due to re-entry to earth and emissions from spacecraft thrusters that lead to global warming and ozone layer depletion, mitigation technologies and pollution prevention methods to reduce OSD, spacecraft shield enhancement, and use of green fuel alternatives to launch spacecrafts with negligible air pollutant emissions.

1. INTRODUCTION

Over the span of six decades, several space related accidents and incidents took place that resulted in the creation of the well-recognized orbital debris cloud that is continually growing.[1] In 2003, the Columbia disaster happened, when the entire crew consisting of seven members died due to the disintegration of the space shuttle upon its entry into Earth's atmosphere.[2] Another accident that took place in space happened with the Russian Soyuz 11 in 1978 during its return to Earth, resulting in the death of all three crew members, after being subject to the explosion of bolts that led to the opening of the pressure equalization valve and consequently caused depressurization.[3] The incident rate is much higher than the accident rate when it comes to space disasters. One of the incidents reported was about the disintegration of the Russian Progress 59 Cargo from the Soyuz.[4] The Progress 59 Cargo began spinning wildly shortly after reaching the orbit and burned up in the Earth's atmosphere.[4] One of the most famous collisions in history that heightened the amount of currently present orbital space debris (OSD) to more than double is the Iridium 33 and Cosmos 2251 satellite collision on February 10, 2009.[5,6] It has been reported that more than 100 000 pieces of nontrackable debris resulted from the impact. Iridium 33 (657 debris) and Cosmos 2251 (1715 debris) contribute to a total of 2372 catalogued debris pieces as of October 2023.[5,6] A major deliberate fragmentation event that shaped the peak in the amount of OSD was the Fengyun-1C collision with an ASAT kinetic-kill vehicle that took place on 11 January 2007, which was reported to increase the OSD by 25%.[5,6] This accident resulted in more than 3525 trackable OSD pieces with sizes ranging more than 10 cm and nearly 40 000 nontrackable ones.[7] On 24 January, 1978, a nuclear spacecraft, namely, Kosmos 954, marked an unplanned re-entry in Canada, scattering radioactive parts of the reactor over 124 000 km^2 of land.[8] Furthermore, a Russian military satellite, namely, Cosmos-2421 collapsed in 2008, generating more than 500 OSD pieces.[9] Additionally, the Russian military communications satellite, namely Raduga-33, resulted in the generation of more than 200 OSD pieces in February 1996 upon the

Received: September 14, 2023
Revised: December 18, 2023
Accepted: December 27, 2023
Published: January 25, 2024

https://doi.org/10.1021/acsomega.3c06887

explosion of its fourth stage booster.[10] Moreover, the cooling loop of the nuclear reactor of the Soviet's reconnaissance satellite, namely, the Radar Ocean Reconnaissance Satellite (RORSAT) spacecraft, leaked a significant amount of coolant droplets in space, resulting in the introduction of a different type of pollutant, i.e., liquid sodium−potassium (NaK) droplets.[11] According to the records, the predicted number of existing NaK droplets during the ejection of the reactor core is more than 50 000, with a size range of 5 mm or more.[11] Although the orbital debris cloud was created due to past spacecraft accidents, remaining debris in the space becomes a threat to other functional satellites present within its orbital region.

The objective of this Review is to examine the type of pollutants, including spacecraft combustion pollution and emissions from spacecraft thrusters that lead to global warming and ozone layer depletion, advance technologies and pollution prevention methods to reduce OSD, and the use of green fuel alternatives, i.e., environmentally friendly alternatives with negligible air pollutant emissions.

2. COMPONENTS AND WORKING MECHANISM OF AN ARTIFICIAL SATELLITE

2.1. General Components of a Satellite.

When it comes to satellite components, depending on their mission and the country manufacturing them, they can vary significantly. In general, satellites consist of several subsystems, i.e., a group of devices comprising numerous individual components.[12] In general, the anatomy of an artificial satellite can be analyzed through eight main components: the station keeping subsystem, the power subsystem (solar panels, batteries, or nuclear energy source), the communication subsystem, the payload (sensors and cameras), the housing, the altitude control system (propellers or thrusters), transponders, and/or the command and data handling component and subsystem.[12−19] Satellites are normally designed and built by considering that maintenance will be avoided as much as possible for their lifespan averaging 15 or more years.[20] Components of the satellite are briefly explained below.

2.1.1. The Station-Keeping Subsystem. The station keeping subsystem is built to keep the satellite on its assigned orbit and orientation to prevent it from colliding with OSD. It maintains the satellite's functionality in case it comes across a shadow phase or if its solar panels are subject to damages due to collision with debris or other satellites.[12,13,16]

2.1.2. The Power Subsystem. The power subsystem mainly comprises solar panels, the battery system, and a power supply and distribution system.[12,16] It is built to supply the satellite with electricity or to generate it and store it when needed to ensure that the satellite's functionality is maintained.[12,13,15,17] The batteries used in satellites are mainly high-performance batteries, and they are primarily made of NaS, NiCd, $NiMH_2$, lithium-ion, or NiH_2.[16,17] Recently, NiCd batteries were replaced with multiple-usage rechargeable $Ni−H_2$ batteries, as they are more practical and durable.[16] The most conventional material in manufacturing solar cells is gallium arsenide, which gives conversion efficiency ranging between 15% and 20% of the total absorbed sunlight.[16] The main components that consume energy are the navigation system, the onboard intelligence (built-in artificial intelligence) system, and the communication and telemetry system.[12]

2.1.3. The Communication Subsystem. The communication subsystem plays a vital role in satellite communication. It operates from Earth, and it functions by sending and receiving the up-link and down-link, respectively, from Earth to the satellite and vice versa. The extracted information could be sold to various clients.[13,16,17] Additionally, the satellite's antennas can provide tracking, telemetry, and control to ensure that the satellite stays in its intended orbit.[16] Studies have shown that if the antennas are impacted, the satellite could potentially be lost, could lose its ability to communicate back with Earth due to the incurred damage, and can further generate small debris (less than 5 cm and less than 0.3 m in LEO and GEO, respectively), which is labeled as non-trackable.[11,16] Depending on its purpose, the antenna is selected and then placed on the satellite before the launch. The reflector antenna is usually accompanied by a beam, and it usually covers only one receiving ground station on Earth; hence, multiple reflector antennas are placed on a satellite to cover a wider range.[17]

2.1.4. The Payload Device Subsystem. The payload device collects the data as per the mission requirements, and with the help of the antennas, this data is transmitted to Earth through radio wave signals.[13,15] Furthermore, the payload can be a collection of sensors and/or cameras, weapon systems, optics, communication systems, or scientific instruments.[12,18] Sensors usually constantly measure the satellite's exact coordinates and send them to the ground station and the satellite's altitude control system (ACS) and propulsion subsystem, which keeps the satellite within its intended coordinates and orientation.[13,21]

2.1.5. Thermal Control and Housing. Thermal control is installed on some satellites to protect them against the continued exposure to space's extreme temperature changes. As the satellites orbit closer to the direction of the Sun, the temperatures become significantly elevated.[12,13,16] Furthermore, due to a satellite's reliance on electrical components within its structure, it is subject to internal buildup of heat, which is usually expelled and radiated off by the help of the thermal control system.[18] The propellers serve as the circulation fans.[17] All satellites are made of a housing/case that brings the internal components of a satellite together, and the cases are sturdy to protect the device against the extreme harsh space conditions as well as the unpredictable but foreseeable space collisions.[13,16,22] The most common satellite housing material can be epoxy−graphite composite and aluminum (and its alloys).[16,17] To help with insulation, the satellite bodies are coated with aluminum-coated polyimide.[17]

2.1.6. Altitude Control System. Additionally, satellites are usually accompanied by an altitude control system, which controls the altitude and position of a complete space vehicle or satellite. Based on this function, the spacecraft orients its solar generators, thermal radiators, thrusters, optical instruments, antennas, etc.[22] Thrusters provide the spacecraft with thrust or the force required to navigate.[19] The thrusters are usually driven by fuel, stored within the fuel subsystem.[19] The most commonly used sources of energy for the engine and thrusters are nitrogen gas, hydrogen gas, hydrazine, kerosene, and liquid nitrogen. These fuels undergo a combustion process to burn the fuel and release the energy for maneuvering the satellite back to track.[16,23] Additionally, plutonium, uranium carbide, and uranium dioxide are the most commonly used nuclear fuels; they undergo a fission reaction under the presence of a compatible propellant, thus triggering a series of chain reactions that release sufficient heat. This heat is then passed on to the propellant, which would be used to navigate the satellite (i.e., as fuel).[24] Low-grade uranium is used in some satellites as a source of energy to generate electricity.[10] Some of these nuclear-powered satellites (NPSs) include Transit 4A, SNAP series (i.e., SNAP-10A), Kosmos series (i.e., Kosmos 954), and others.[25−27]

2.1.7. Other Essential Components. Satellites consist of transponders that work on changing the frequencies of electronic signals generated from uplink to downlink and vice versa, i.e., from the signal traveling upward from Earth's surface to the satellite and from the signal traveling downward from the satellite to Earth's surface.[13,16,19,22,28] There are three types of transponders: passive, simple active, and sophisticated active.[16,29] Passive transponders activate through nearby scanners or antennas as their source of power to function and transmit the requested information upon receiving a response from the scanner nearby.[29] Simple active transponders utilize their internal battery to power up and operate, whereas sophisticated active transponders receive signals from a band of multiple frequencies and are incorporated in communication satellites and space vehicles.[29] The command and data handling component and control subsystem consists of a telemetry, tracking, and control system, which consists of ample computers that gather and process data and communicate with other components to execute and obtain commands from Earth's ground stations and perform the predetermined satellite missions and operations.[12,13,16] Additionally, it is responsible for monitoring the satellite's health and functionality and its operational conditions.[21,22]

2.2. General Working Mechanism of a Satellite. The general working mechanism of a satellite, regardless of its type and dictated mission, utilizes the fuel reserve to reach the destined orbital track. Upon arrival, gravitational force acts on it to take over control and set it in orbit.[24] There are several factors and forces that can act on a satellite and affect its intended trajectory and angle of orientation, including the sun's gravitational force, the moon's gravitational force, other space debris heading uncontrollably toward the satellite, a malfunction in the solar panels due to shadow phase or damages due to collision with OSD, malfunction of the batteries due to overuse, or any other causes resulting in cutoffs to sunlight access.[12,13,16] When the satellite succeeds in reaching its specific orbit at a high speed due to the presence of gravitational forces, its carried mass, and the lack of air-friction in space, the satellite becomes attracted to the intended planet or star.[30] If sufficient momentum is sustained, the satellite starts to orbit the other object of a larger mass.[30]

Depending on the components shaping it and on the missions it was created for, a satellite's working mechanism can vary. Initially, the device communicating with the satellite from Earth's surface creates an uplink to be sent to the satellite in space.[19,20] Consequently, with the help of the satellite's transponders,[29] the uplink is received and amplified, and the frequency is then converted to a downlink.[20] Subsequently, the downlink is sent back to Earth's receiving device located on a specific geographical location.[19]

In order to keep a satellite in its intended orbital track, a satellite can be maneuvered with the help of the fuel stored in the station keeping subsystem.[16] The satellite combusts the stored fuel only in case it goes off track. The combusted fuel is usually ejected from the thruster's nozzle.[16] The fuel stored undergoes a combustion process in the engine, thus providing the rocket with sufficient force (thrust). The heavier the launched spacecraft is, the longer the combustion process will be to account for the weight of the object and to navigate.[31,32] Consequently, the satellite's propulsion system creates thrust that keeps the satellite in motion, and the thrust force is adjusted depending on the mass of the satellite.[31,33] The thrust force is defined by the difference between the thrust propulsion force and the drag force acting on the satellite. When an excess thrust is reached, acceleration will be initiated.[31−33] In order for satellites to maintain their existence in space, a force balance must be ensured between the centrifugal force and the gravitational force, i.e., the centrifugal force acting on the satellite in an outward manner and Earth's gravitational force inducing an inward pull toward the earth.[12]

Functional satellites remain in orbit once they are launched into space. Satellites are launched at specific predetermined orbital trajectories, and their payload, guidance and stabilization, and station keeping subsystems ensure that they do not get out of this track. By performing the required maneuvers to adjust in case of any potential collisions, these systems ensure that the satellite is in its orbit path.[15,16] Besides ensuring that the satellite is kept in its dedicated orbit, spin-stabilized systems also keep the satellite pointed toward its planned orientation and direction by ensuring that its antenna is pointing toward the intended direction.[16]

3.0. COSMIC AND SPACE POLLUTION

3.1. Space Light Pollution. According to Wall, anthropogenic activities resulted in a 10% increase in light pollution in the space atmosphere, and astronauts reported that this pollution can be seen without the help of any magnifying devices, resulting in disruption to their work due to spacecraft light trails.[4] The currently reported night sky pollution already exceeded the allowable limit set by the International Astronaut Union (IAU), even without further spacecraft launches.[6] These anthropogenic activities that result in night sky pollution and space discovery hindrance are mainly due to the increasing number of commercial satellites in low earth orbit (LEO), the artificial light at night, and the radio-broadcasting effects from both the land and space signals.[34]

Out of the 5500 active satellites currently present in space, the ones in LEO have been reported as plainly visible above the horizon at low elevations on Earth, at twilight, and dawn.[34] Additionally, nearly 30−40% of the images generated by wide-field telescopes are believed to be wasted on capturing the upcoming satellite constellations in motion rather than capturing moving objects, as intended.[34] The increase in artificial light at night has led to the deterioration of the health of biotic species by affecting the bioenvironment, the degradation of the aesthetic view of the night sky, and cosmic observation hindrance due to excessive lighting.[34]

3.2. Anthropogenic and Nonanthropogenic Pollutants and Stratospheric Ozone Depletion. The causes of stratospheric ozone layer depletion include the release of atmospheric pollutants to the stratosphere from satellite thrusters while traveling toward the destined orbital track, the incineration of OSD as it is falling back to Earth, and the accidental release of persistent pollutants into the stratosphere from the satellite's cooling system.[6,35,36] The way these pollutants decompose the ozone molecules is either by directly or by indirectly reacting with them through enhanced Cl-activated ozone reactions, which result in chlorine molecule binding to the ozone molecules.[35] The molecules that result in Cl activation reactions are CH_4, Al_2O_3, and HCl. Chlorine radicals mainly result from the evaporation of marine and oceanic waters that carry dissolved salt (NaCl), which transfer to the atmosphere in the form of suspended solids.[37] Upon their transfer to the upper atmosphere, the NaCl molecules react further with atmospheric gases including NOx. This results in the generation of Cl_2 molecules that get in contact with sun rays, thus breaking them into Cl radicals.[37]

There are four main types of fuel systems or sources: solid rocket motors (SRMs), liquid rocket engines (LREs), hybrid rocket engines (HREs), and nuclear power sources (NPSs).[6,10,35,38] Each of them is accompanied by a specific compatible type of fuel, and the main types of fuels include hypergolic fuels, solid fuels, kerosene, and cryogenic fuels (liquid hydrogen).[35] In addition to the fuel system, the propulsion system of most satellites consists of a supporting oxidizer. Each of these fuels, when combusted, results in different emissions in the atmosphere. For instance, hydrazine, i.e., N_2H_4, H_2NNH_2, H_2N-NH_2, or H_4N_2, when used as a fuel, results in H_2O and NOx emissions, whereas hydrocarbon fuels, liquid NOx oxidizers, and kerosene-based fuels release NOx, black carbon, and H_2O into the atmosphere.[16,23,35] Three main compounds that act as oxidants that supply oxygen to the reactions are OH and O_3, followed by NO_3.[37]

The safest in terms of byproduct emissions is the nuclear reactor, as it results in no direct emissions; however, it is the most dangerous to eradicate, as the molecules remain highly radioactive for hundreds and thousands of years, depending on the decaying element used in the reactor. Although it has not been reported that these molecules have any direct impacts on the atmosphere, these molecules, if released due to leakage or OSD collision at extremely high velocities, set potential risks of having them travel past the stratosphere and consume the ozone molecules present within their vicinity. This possibility of risk is valid if the satellite was destined to orbit the LEO region, i.e., at a close distance to Earth.[10]

The space is currently polluted with more than 50 000 sodium−potassium (NaK) metal droplets of a diameter sized 5 mm or more, which were leaked from the cooling loop of the Russian satellite's nuclear reactor (RORSAT).[11] Solid rocket fuels are considered the worst in terms of space emissions, as they result in the generation of not only Al_2O_3 but also sulfate oxides, etc.

Alumina pollution (Al_2O_3) from solid rocket motors (SRM) results in two distinct sources, SRM dust (which ranges in size from 1 to 50 μm), and SRM slag, which results in particles up to a few centimeters in size. Emission of these particles in space at high velocities can result in potential collision threats with other space objects, leading to an expansion in OSD cloud volume.[11]

As a result of the ongoing fuel combustion process within the satellite's propulsion system, several types of atmospheric pollutants are introduced into the atmosphere. Some of these pollutants include Al_2O_3 molecules ejected from the thruster's nozzles, leaked slag and unburnt fuel (up to 5 mm diameter in size), H_2O vapors, CO molecules, CO_2 molecules, NOx molecules, volatile organic compounds (VOCs), Cl, and methane (CH_4). Additionally, metals including silver, magnesium, nickel, sodium−potassium alloys (NaK), copper, calcium, silicon, gold, lead, iron, tin, and titanium, as well as plastics and composites, have been reported to be released in negligible quantities compared to all the other pollutants.[11,31,33,35,37,38] These metals and plastics mainly originate from the satellite's body. However, NaK is a result of the leak from RORSAT's cooling loop. NaK is highly corrosive and ignitable and can result in an explosion upon any interaction with air or water, which are readily available and constantly emitted into space.[11,39] Besides, corrosive properties allow for the formation of more OSD, which feeds into the loop of increasing the OSD cloud volume upon its contact with the bodies of other satellites. The formation of Al_2O_3 through propellant ejection results in the formation of other OSD, namely, slag and unburnt fuel, due to the constant expansion and solidification process.[38] Furthermore, Al_2O_3 is a major contributor in increasing the OSD cloud, as it reacts with the bodies of satellites, causing them to corrode and degrade into further OSD.[11]

Regardless of the type of fuel combusted, H_2O vapors and NOx are inevitable; however, Al_2O_3 and gaseous Cl_2 only result from solid fuel, and black carbon results from the combustion of kerosene, hypergolic fuels, and solid fuels.[11,35] When exposed to elevated temperatures, NOx gases (i.e., NO, NO_2, and/or N_2O) oxidize to form HNO_3, especially when a ratio of HNO_3/NO is maintained between 0.6 and 1.3.[35,39] NO_3 is mainly active during the nighttime, and it results in the formation of H_2O and $R-O_2$ organic compounds.[37] Most of these pollutants result in the degradation of ozone molecules.

It has been known that both black carbon and Al_2O_3 work on altering the atmospheric radiative balance of Earth, at which the incoming radiation rate exceeds the one leaving it, resulting in global warming.[35] Black carbon absorbs the shortwave radiation, whereas Al_2O_3 absorbs the longwave radiation. H_2O and CO_2 also contribute toward a minor global warming effect.[35] The study conducted by Ryan et al. estimated the overall global radiative force in three years from 2019 as +3.9 mW/m.[2,35] They predict this value to double to nearly +7.9 mW/m^2 by accounting for space tourism flights expected to take place within three years following 2019.

Depending on the type of hydrocarbon fuel, the combustion temperature, pressure, and reaction conditions, VOCs can significantly vary. VOCs react with the oxidants present to form various products. For instance, alkanes, upon their release with the exhaust plumes, react and primarily form OH, NO_3, and trace amounts of Cl radicals. Alkenes, however, mainly react with the compounds in space to form OH, O_3, NO_3 ,and Cl radicals. Alkynes and aromatics are similar, as they result in the formation of OH and Cl. Aldehydes result mainly in the formation of OH, NO_3, Cl, and H_2O. The study points out that complex side reactions are present through decomposition and/or recombination reactions or by reacting with OH.[37]

Fuel combustion, marine water evaporation, and Al_2O_3 and CH_4 molecules are the major contributors toward the formation of chlorine, which gets involved with chlorine-activated ozone molecules.[35,37] The total reported amount of depleted ozone is between 0.01% and 0.1% of the total stratospheric ozone present, solely due to solid rocket motors (SRM) emissions, and it is estimated that nearly 6% O_3 destruction will result from emissions due to the launch of only 1000 hybrid rocket engines (HREs) to space, which is anticipated to increase the polar temperature by 1 °C.[6]

It has been observed that slag is mostly a waste product emitted from solid rocket engines, and it is mostly emitted at an approximate quantity of 0.65% of the initial fuel's mass, which is significantly high, especially as it accumulates over the years.[38] As a result of engine combustion, thousands of dust particles are emitted along the way, which are proven to lower the optical properties of spacecraft components that are essential for functioning adequately to accomplish the

Table 1. Main Pollutant Emissions, Fate of Pollutants, and Outcomes

source of emissions: atmospheric exhaust emission

main type of pollutant	fate of pollutant upon its release	outcome of reactions	ref
ClO, BrCl, ICl, Cl, Cl_2O_2, HOCl,ClOO, Cl_2, OClO, and $ClNO_3$	enhanced Cl-activated O_3 reaction	Cl	35
HCl	enhanced Cl-activated O_3 reaction and re-entry burning		
NOx	re-entry burning	O_3 depletion	35
	direct reaction with O_3	R−O_2	37
		H_2O → PSC formation → O_3 depletion	
		HNO_3 (if HNO_3:NO = 0.6:1.3)	35
VOCs (including alkanes, alkenes, aldehydes, and alkynes)	optical hindrance		53
	VOC and OH Side reactions	decomposition/recombination reactions → O_3 depletion	37
VOCs: alkanes	direct reaction with O_3	Cl•, OH, NO_3	
VOCs: alkenes		Cl•, OH, NO_3, O_3^-, O_3	
VOCs: aldehydes		Cl•, OH, NO_3, H_2O	
VOCs: alkynes		Cl•, OH	
Dust	10 × 10^{20} particles emitted/combustion cycle @ 1.5−3.5 Km/s	colliding OSDs and optical observation hindrance	38
Cl_2	direct reaction with O_3 and enhanced Cl-activated O_3 reactions	Cl.: 49% O_3 depletion during spring	35
black carbon (BC)	direct reaction with O_3 enhanced Cl-activated O_3 reactions and re-entry burning	dark and light colored BC: 500× global warming effect of other pollutants, change in global radiative forcing	35, 42
Al_2O_3	direct reaction with O_3	slag → equivalent to 0.65% of initial fuel mass	11, 38, 44
		altering Earth's albedo	
		satellite corrosion	
		altering Earth's radiative forcing	
		O_3 depletion	
		altering Earth's geoengineering features	
	enhanced Cl-activated O_3 reactions (if Al_2O_3 diameter is between 0.01 and 1μm)	O_3 depletion	35
	re-entry burning emission	altering Earth's albedo	35, 44
		O_3 depletion	
		altering Earth's geoengineering features	
CH_4	direct reaction with O_3	global warming and O_3 depletion	35
	enhanced Cl-activated O_3 reactions	OH → VOC side reactions → global warming	35
Br, N, Cl, H and their oxides	100 000 O_3 molecule destruction/1 radical	O_3 depletion	6
COx	global warming		35
HONO	photolysis	OH → VOC side reactions → global warming	35, 37, 41, 42
H_2O	direct reaction with O_3	PSC formation →O_3 depletion	37

source of emissions: atmospheric exhaust emission and NaCl evaporation and transport from troposphere to stratosphere

main type of pollutant	fate of pollutant upon its release	outcome of reactions	ref
Cl•	enhanced Cl-Activated O_3 reactions	O_3 depletion	35, 37

source of emissions: accidental leakages in cooling system, discarded batteries, nuclear fuels in LEO orbit, and collision remains

main type of pollutant	fate of pollutant upon its release	outcome of reactions	ref
low-pressure ionic liquid droplets	O_3 depletion		11, 36
50 000+ NaK metal droplets	satellite corrosion reactions with H_2O and air	O_3 depletion	11,39
others: Si, Ni, Mg, Cu, Ca, Ag, Au, Pb, Fe, Sn, Ti, plastics. and composites	colliding OSDs		11, 38

predetermined mission.[38] One combustion cycle can result in the formation of up to 10^{20} dust particles, ejected at an average velocity of 1.5 to 3.5km/s, depending on the particle size.[38]

Several space studies confirm that the amount of O_3 degradation due to space launches is insignificant, especially when compared to the pollution levels attributed to CFCs and ozone-depleting substances released on Earth.[6,35] Out of all the pollutants described previously, black carbon is ranked as the worst, as it can contribute to global warming up to 500 times the warming effect of all the other pollutants emitted from spacecraft rockets.[35] This is followed by alumina and radicals. Alumina has the ability to increase the warming effect by nearly 16 ± 8 mW/m^2.[6] Radicals including Br, N, Cl, and H, along with their oxides, are highly reactive to the extent where one molecule is effective in destroying nearly 100,000 O_3 molecules.[6]

When analyzing the effects of H_2O on the stratosphere, two main adverse impacts have been identified: the formation of polar stratospheric clouds (PSCs), or nacreous clouds, and their resultant global warming caused by reacting with other gaseous constituents to deplete O_3.[40−42]

Some satellites rely heavily on coolants in order to waive off the accumulated heat that is constantly generated within the satellite due to the presence of electric components. According to the Federal Communications Commission, most of these coolants evaporate as they escape the satellite and vanish in space, eliminating any traces of potential threats of expanding the currently present OSD cloud.[36] However, some types of liquid coolants utilized in the cooling process, including low-pressure ionic liquids, have been reported to remain as live droplets, which will be set in orbit at high speeds and act as threatening OSD.[36] In addition to these, discarded batteries and other intrinsic components that disconnect from a satellite are subject to explosion and loss in space.[38] As a result, postexplosion residues will result and will add up to the packed OSD cloud.[38]

3.3. Burning of Spacecraft Re-Entering Earth and Its Accompanying Pollution. Satellites that manage to re-enter Earth's atmosphere are subject to gravitational and frictional forces, and each of these forces will work in parallel to act on the re-entering OSD to pull it down to Earth, decrease its speed, and execute the incineration process due to air friction.[43,44] Spent rockets either land on Earth's surface to be reused or disintegrate in Earth's atmosphere due to air friction.[35] Upon the re-entry of OSD, it has been observed that the pollutant emitted to the atmosphere at the highest quantities is NOx,[35] followed by Al_2O_3. In contrast, the pollutant emitted at the highest quantities due to rocket plume emissions at nearly fifteen km is H_2O, followed by Al_2O_3, followed by HCl and chlorine gases, followed by black carbon, and last followed by NOx.[35] It has been reported that nearly 95% of the total amount of NOx released is due to re-entry, whereas nearly 78−79% of the total amount of H_2O and black carbon and nearly 68−69% of the total amount of chlorine and Al_2O_3 are emitted in the atmosphere from the process of launching rockets to space.[35] This is shown to have a direct negative effect on climate change due to global warming and ozone layer depletion.[44]

Another study analyzed the atmospheric pollution in the stratosphere specifically, at which it was concluded that the pollutants emitted due to spacecraft incineration in the atmosphere results from the vaporization of the metals present in spacecraft components; these metal particles are believed to integrate with the meteoric dust naturally present in the various atmospheric layers.[45] Although the effects of metal vapors were said to be ambiguous, it is predicted that the accumulation and condensation of metallic vapors near the north and south poles of Earth is probable, which would eventually lead to the deposition of snow that is contaminated with heavy metals.[45] The study also reports high chances of probable optical hindrance due to the existence of these particles in the atmosphere.[45]

Table 1 summarizes the main pollutants emitted along with their sources of emission, probable fates, and associated effects. Figure 1 below provides a visual mapping of these pollutants from previous studies[6,10,11,16,23,31,33,35−38,41−44,53] while highlighting their trajectory and circulation path in depth.

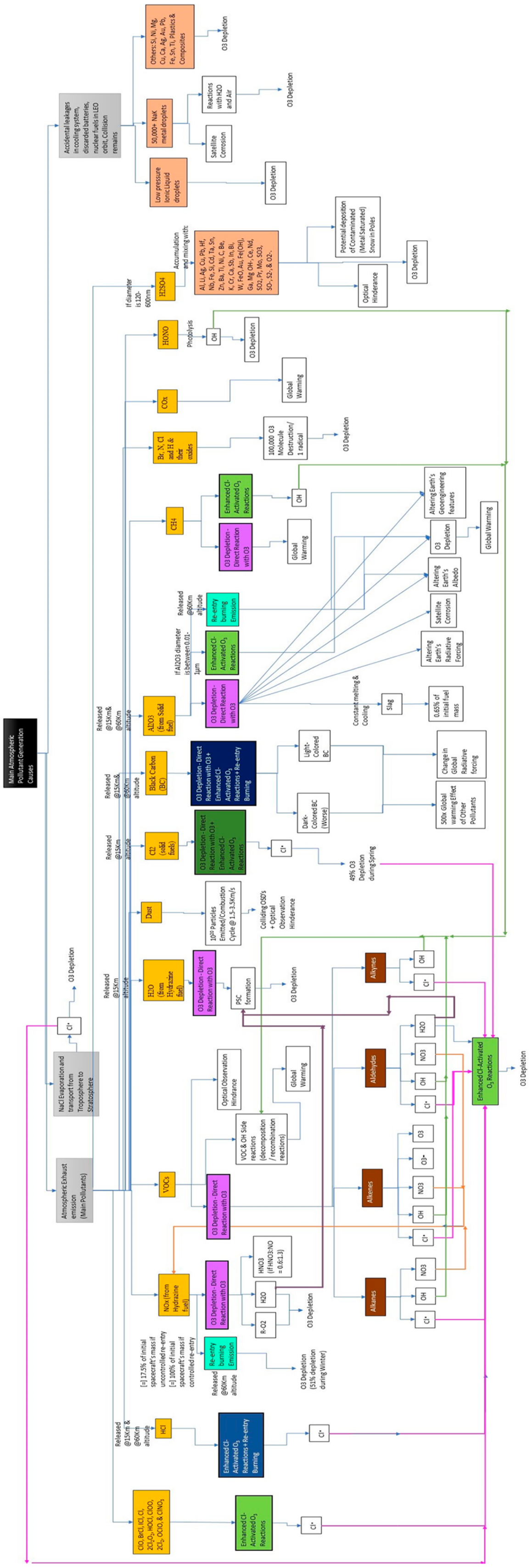


Figure 1. Main Atmospheric Pollutant Emissions, their Reactions, and their Fates* (*from References:[6,10,11,16,23,31,33,35−38,41−44,53]).

4. MITIGATION AND POLLUTION PREVENTION TECHNIQUES FOR PROTECTION AGAINST OSD

In order to address the alarming and rising space pollution, governments have proposed many regulatory measures and mitigation measures, including active debris removal (ADR), to both existing spacecrafts and new ones to be launched.

The most common regulations issued on limiting further growth of OSD are the following: UN Space Treaty, 1967; The Convention on International Liability for Damage Caused By Space Objects, 1972; The European Cooperation in Space Standards; ISO 24113:2011 replaced by ISO 24113:2019, Space debris mitigation requirements; The United Nations Committee on the Peaceful Uses of Outer Space (UN-COPUOS), Space Mitigation Guidelines; Inter-Agency Space Debris Coordination Committee (IADC) Mitigation Policies and Practices; U.S. Government Orbital Debris Mitigation Standard Practices, 2001; and NASA orbital debris mitigation guidelines, 1995.[6,10,46,47]

ADR technologies or pollution prevention (source reduction) are either planned, tested, or implemented to protect the current spacecraft present in space, mostly in LEO and GEO, as well as to limit further growth of OSD, and these include utilizing green fuel instead of regular spacecraft fuel, shielding against OSD, and active debris removal (ADR). Table 2 summarizes the ADR technologies or pollution prevention (P2) methods, along with their advantages and disadvantages.

4.1. Sustainable Green Fuel Alternative: Pollution Prevention. The most commonly used spacecraft fuel is hydrazine, which is known for its ample atmospheric emissions. The modern solution to limiting the harmful emissions is using green fuel, i.e., an environmentally friendly fuel associated with minimal atmospheric emissions, referred to as AF-M315E, to refuel spacecraft.[48] Its physical and chemical properties vary significantly from common spacecraft fuels, which tend to have a higher viscosity but require minimal safety measures upon refueling, storing, transporting, and accidental spillage.[48] AF-M315E is an ionic liquid composed of hydroxyl ammonium (HAN), water, and other nonionic liquids. It has the ability to remain liquid and turn into glass at extremely low temperatures in space (nearly −80 °C) instead of freezing, and it is less toxic than hydrazine and hydrocarbon fuels.[48,49] AF-M315E is known for its negligible vapor pressure and its high solubility, which limits the need for high safety requirements especially for storage and handling by requiring only single-fault tolerance when handling flight systems.[49] Hence, a lower cost is required for manufacturing storage tanks, as AF-M315E has a relatively high viscosity and negligible vapor pressure compared to hydrazine, which minimizes its chances to leak in case of cracks or faults in valves.[49] The only disadvantage of using it over hydrazine and carbon fuels is that it has twice the combustion temperature of hydrazine, which results in increased energy to heat it up; however, by weighing the pros and cons of using it, one can conclude that atmospheric emissions are a major threat to the space environment, knowing that there will be a sharp peak in the number of spacecraft to be launched over the coming years. Further improvements have been done to convert AF-M315E to a greener fuel, and Air Force Research Laboratory (AFRL) invented Advanced Spacecraft Energetic Nontoxic (ASCENT) propellant, which has 50% higher impulse density than hydrazine.[49,50] ASCENT is manufactured to have a decreased vapor pressure and low reactivity compared to hydrazine at atmospheric conditions, which eventually yields lower safety requirements.[50]

4.2. Shielding Specific Modules of a Functional Satellite: Pollution Prevention. Depending on the size of the OSD threatening an active functional satellite, mitigation measures are planned and executed accordingly. For instance, for debris sized 10 cm or more, satellites have the tendency to opt for "debris avoidance maneuvers", which are when satellites maneuver from their orbital track to avoid the collision. As for debris of a smaller size, shielding on the satellites can be used upon unanticipated collisions.[51] This causes the debris to collide into the shielding material only, keeping the satellite parts intact. However, depending on the size of the debris and the quality of shielding material and its placement, the satellite can still be subject to damage. The International Space Station (ISS) executed a total of 29 maneuvers up to 2020 and is considered the most shielded spacecraft in space.[11,51]

Several materials can be used to protect the satellites from radiation and the elevated temperatures in space, leading to fragmentation generation, including composites, aluminum, and polyethylene. Martinez studied these materials and tested them against simulation results in order to verify their durability against the radiation in space.[52] Composites and polyethylene are the most common materials that can be used to protect satellites from radiation and ionosphere molecules.[52] Composites block the radiation and inhibit particle formation upon exposure to radiation, whereas polyethylene contains numerous hydrogen molecules that work on absorbing the radiation upon exposure.[52]

In addition to this, the first and the most famous shield that has been implemented is the Whipple Shield, which was invited by Engineer Fred Whipple to protect spacecrafts from threatening OSD ranging up to 1 cm in diameter.[11] OSDs vary in nature from black carbon particles to paint flakes to VOC particles that cool and condense on cool windshields of spacecraft. VOCs evaporate due to the exposure of the space vacuum and consequently face uneven solar radiation, mainly due to outgassing process, causing them to condense on cooler surfaces such as satellites' camera lenses and windows.[53] The Whipple Shield consists of a thin decaying wall, referred to as the bumper, that is installed to keep a distance between it and the satellite's body, and the shield is known for its lightweight and its effectiveness, especially when colliding with OSD particles that have the potential to result in a hypervelocity impact.[11]

In addition to composite shielding, polyethylene shielding, and the Whipple shield, there are three main types of organic polymeric coatings that could be applied to minimize the amount of erosion taking place on the satellite's surface as much as possible, including polysiloxane polymers, polysilazane polymers, and fluorinated polymers.[54] Out of these three, the top ranked protective coating is the polysiloxane polymer coating, as it has high resistivity and binds to a remarkably high degree.[54] Other inorganic coatings include SiO_2 and Al_2O_3, which are also known for their poor adhesive properties.[54] Perhydropolysilazane-derived SiOx (PHPS) coating, as founded by Qi et al., is a gradient coating that enforces gradient structure and composition by reacting with a moist and cold environment to harden as a top-isolating coating on the body of a spacecraft, which provides a high level of protection against atomic oxygen for 48 years.[54]

Table 2. Main OSD Mitigation Technologies or Pollution Prevention (P2) Methods and Their Associated Advantages and Disadvantages

		OSD Mitigation technologies/P2 methods	advantages	disadvantages	ref
1	sustainable green fuel alternative	AF-M315E (compared to hydrazine)	they address the propellant toxicity on ground and in space	has twice the combustion temperature of hydrazine	48, 49
			consists of nearly half of the components, but with a reciprocated high performance	requires higher energy to heat it up	
			negligible vapor pressure and high viscosity thus minimal chances to leak	higher cost	
			lower toxicity		
			remains liquid and turns into glass at low temperatures in space instead of freezing		
			high solubility		
			minimal safety requirements for refueling, storing, transporting, and accidental spillage cleanup		
			requires lower storage tank manufacturing costs		
			requires no PPE to be worn by astronomers while handling it, thus lower cost spent		
			lower atmospheric emissions		
			lower OSD depletion		
			lowering global warming contributions		
		advanced spacecraft energetic non-toxic (ASCENT) propellant	lower atmospheric emissions	high cost to generate	50
			has 50% higher impulse density than that of hydrazine		
			decreased vapor pressure		
			low reactivity		
			low safety requirements		
			lower OSD depletion		
			lowering global warming contributions		
2	spacecraft shielding	composite	provides spacecraft protection against radiation and ionosphere molecules	does not eliminate current OSD	52
			reduces further OSD growth		
			blocks radiation and inhibits particle formation upon exposure to radiation		
		polyethylene	provides spacecraft protection against radiation and ionosphere molecules	does not eliminate current OSD	52
			absorbs radiation upon exposure		
			reduces further OSD growth		
		whipple shield	lightweight		11
			effective in spacecraft shielding against OSD		
		organic polymeric coating (polysiloxane polymer coating)	minimizes corrosion on satellite bodies	does not eliminate current OSD	54
			provides protection against atomic oxygen		
			has high resistivity		
			binds to a high degree		
			reduces further OSD growth		
		organic polymeric coating (perhydropolysilazane-derived SiOx (PHPS) coating)	enforces gradient structure and composition	does not eliminate current OSD	54
			reduces further OSD growth		
			provides a high level of protection against atomic oxygen for 48 years		

Table 2. continued

	OSD Mitigation technologies/P2 methods	advantages	disadvantages	ref
	Inorganic coating (Al2O3 Coating and SiO2 coating)	reduces further OSD growth	does not eliminate current OSD	54
			poor adhesive properties	
3	natural aerodynamic decay	natural atmospheric incineration	only achieved if the spacecraft is located less than 800 Km from Earth's surface	15, 55, 56
		cost-effective	cannot target multiple OSD simultaneously	
		reduces OSD collision risk by eliminating target satellite/OSD	generation of atmospheric pollutants (NOx, HCl, BC, and A_l2O_3) → re-entry burning	
			O_3 layer depletion and global warming	
			change in global radiative forcing	
			altering Earth's albedo, geo-engineering features due to Al_2O_3	
			satellite corrosion → OSD cloud growth	
4	drag sail deorbiting	equipped with telemetry and electrical equipment and fail-safe tool to reinforce a controlled landing toward the earth	cannot target multiple OSD simultaneously	55
		Natural atmospheric incineration	generation of atmospheric pollutants → re-entry burning)	
		Reduces OSD collision risk by eliminating target Satellite/OSD	polar stratospheric cloud formation → global warming	
			O_3 layer depletion	
			change in global radiative forcing due to BC and Al_2O_3	
			altering Earth's albedo and geo-engineering features (due to Al_2O_3)	
5	net deorbiting	natural atmospheric incineration	Cannot target multiple OSD simultaneously	55
		launches an inflatable balloon connected to a net, which captures the satellite	Generation of Atmospheric Pollutants	
		reduces OSD collision risk by eliminating target satellite/OSD	Polar stratospheric cloud formation → Global warming and O3 layer depletion	
			Change in global radiative forcing and altering Earth's albedo (due to Al2O3)	
			Altering Earth's Geo-engineering Features (due to Al2O3)	
6	harpoon deorbiting	reduces OSD collision Risk by eliminating target satellite/OSD	cannot target multiple OSD simultaneously	55
		utilizes a harpoon fired toward the targeted spacecraft to capture it and induce planned atmospheric incineration	generation of atmospheric pollutants	
		can be equipped with a tether to induce a planned landing	polar stratospheric cloud formation → global warming (due to H_2O)	
			O_3 layer depletion and global warming	
			change in global radiative forcing, altering Earth's albedo and geo-engineering features due to Al_2O_3	
7	client servicer deorbiting	reduces OSD collision risk by eliminating target satellite/OSD	impossible in future as satellites become magnetically neutral	55
		composed of a client spacecraft and a servicer spacecraft to search for OSD and deorbit them	does not work on non-Magnetic OSD	
		can utilize a magnetic tug to deorbit OSD in a graveyard orbit	generation of atmospheric pollutants	
		reduces current OSD cloud	polar stratospheric cloud formation	
			global warming and O_3 layer depletion	
			if OSD is deorbited in graveyard orbit then potential and eventual crowding of graveyard orbit and further growth in OSD Cloud	
			if OSD is deorbited in Earth's atmosphere, then generation of atmospheric pollutants → re-entry burning, O_3 layer depletion and global warming, change in global radiative forcing and altering Earth's albedo and geo-engineering features	
8	magnetic space tugs	reduces OSD collision risk by eliminating target satellite/OSD	impossible in future as future satellites are magnetically neutral	57
		can be used to target multiple OSD simultaneously	Does not work on nonmagnetic OSD	

Table 2. continued

		OSD Mitigation technologies/P2 methods	advantages	disadvantages	ref
			reduces current OSD cloud	if OSD is deorbited in graveyard orbit then there is a potential and eventual crowding of graveyard orbit	
			can deorbit OSD in a graveyard orbit magnetically	if OSD is deorbited in Earth's atmosphere, then generation of atmospheric pollutants, re-entry burning, O_3 layer depletion and global warming, change in global radiative forcing and altering Earth's albedo and geo-engineering features	
9	chemical propulsion deorbiting	gaseous/liquid chemical propulsion	reduces OSD collision risk by eliminating target satellite/OSD	cannot target multiple OSD simultaneously	58, 59
		solid chemical propulsion	utilizes thrust generated from exothermic chemical reactions to deorbit satellites	heavily relies on stored fuel → subject to depletion → increased OSD generation and collision risk	
		hybrid chemical propulsion	highly efficient → generate a huge amount of thrust in a short duration	expels heat	
			can deorbit OSD in a graveyard orbit	Generation of atmospheric pollutants → Exhaust emissions	
				Polar Stratospheric Cloud formation → Global Warming	
				O_3 layer depletion and global warming	
				if OSD is deorbited in graveyard orbit, then potential and eventual crowding of graveyard orbit and further growth in OSD cloud	
				if OSD is deorbited in earth's atmosphere, then generation of atmospheric pollutants → re-entry burning, O_3 layer depletion and global warming, change in global radiative forcing, and altering Earth's albedo and Geo-engineering features	
		electrical propulsion deorbiting	reduces OSD collision risk by eliminating target satellite/OSD	inefficient due to reliance on satellite's storage of solar energy	58
			can consume solar energy to deorbit → green alternative to fuel	weak thrust generation compared to chemical propulsion → risk of running out of power to deorbit → OSD collision and generation risk	
			minimized exhaust emissions upon deorbiting	Generation of atmospheric pollutants → Re-entry Burning)	
			utilizes electrical field, magnetic field, or electrical heating system to deorbit	O3 layer depletion and global warming,	
				change in global radiative forcing (due to BC and Al_2O_3)	
				altering Earth's albedo and altering Earth's geo-engineering features (due to Al_2O_3)	
10		electrodynamic tethers	reduces OSD collision risk by eliminating target satellite/OSD	cannot target multiple OSD simultaneously	55−60
			utilizes electromagnetic tether → generates electromagnetic force to deorbit OSD to Earth's electromagnetic field	generation of atmospheric pollutants → re-entry burning)	
				O3 layer depletion and global warming	
				change in global radiative forcing (due to BC and Al_2O_3)	
				altering Earth's albedo and geo-engineering features (due to Al_2O_3)	
11		laser	reduces OSD collision risk by eliminating target satellite/OSD	cannot target multiple OSD simultaneously	61
			utilizes radiation pressure emitted from a laser light to deorbit OSD	OSD's new orbital track and direction must be predetermined	
			can deorbit OSD in a graveyard orbit	upon the occurrence of a mistake in the process, OSD can become nontrackable	
				requires customization of the firing laser beam per OSD	
				risk of expanding the OSD cloud further upon burning the OSD	
				requires analyzing the surroundings before firing the laser beam	
				cannot target multiple OSD simultaneously	
				if OSD is deorbited in graveyard orbit: potential and eventual crowding of graveyard orbit and further growth in OSD cloud	
				if OSD is deorbited in earth's atmosphere: generation of atmospheric pollutants, re-entry burning, O_3 layer depletion, and global warming	
				change in global radiative forcing	
				altering Earth's albedo and altering Earth's geo-engineering features (due to Al_2O_3)	

Table 2. continued

	OSD Mitigation technologies/P2 methods	advantages	disadvantages	ref
12	long-term satellite servicing	reasonable and effective solution maintenance and refueling of targeted satellite → reducing need for deorbiting reduces OSD collision risk by eliminating target satellite/OSD	does not eliminate current OSD subject to inefficient maintenance → chance of collisions with other satellites or OSD	15

4.3. Active Debris Removal (ADR): OSD Mitigation. It is essential to note that existing mitigation measures have been already applied to ensure repairing, refueling, or upgrading the already existing spacecrafts in situ, and only limited ADR target defunct satellites but do not actually deal with the remaining present debris. It is noted that deorbiting takes place by directing the target objects either toward graveyard orbits or toward earth for a controlled or uncontrolled atmospheric incineration. Each of these technologies is discussed below.

4.3.1. Natural Aerodynamic Decay. According to space waste management regulation, no country should keep its launched satellite after its end of life for a period exceeding 25 years; however, this set of legislation has been changed and the satellite's allowable end of life in space period has been reduced to 5 years.[53] Natural aerodynamic decay is the process of inducing the natural decay of a satellite by bringing it closer to Earth's surface to induce natural atmospheric incineration.[15,56] This method is considered cost-effective, as it can be done with the help of a physical tool such as a net, an air bursting tool, or a drag sail (boom) to push the defunct satellite to a lower altitude toward Earth's surface.[15,56] This can only be achieved if the spacecraft is located at 800 km from Earth's surface or less.[55]

4.3.2. Drag Sail Deorbiting Technology. The drag sail functions with the help of sail films divided into multiple modules, where each module provides the satellite with a drag area to help with the landing toward Earth's atmosphere so that it is subject to incineration in a passive manner.[55] Each individual module is generally equipped with telemetry and electrical equipment to reinforce a controlled landing toward Earth as well as a fail-safe tool in case of a module's failure.[55] A common example combining both passive drag sail system and controlled re-entry is the Exobrake, a braking system used to support the navigation of the spacecraft to lower its altitude toward Earth.[55]

4.3.3. Net-Capturing Technology. Another technology involves launching a spacecraft ahead of a satellite required for deorbiting. As the spacecraft approaches the target satellite, it begins to launch an inflatable balloon connected to a net that captures the satellite required for deorbiting in order to direct it toward Earth's surface to induce a planned atmospheric incineration.[55]

4.3.4. Harpoon-Capturing Technology. In addition to these, another technology utilizes a harpoon, fired toward the targeted spacecraft to capture it and direct it toward Earth, in an active (nonpassive) manner to induce a planned atmospheric incineration and the deorbit of the debris.[55] Initially, a spacecraft carrying the harpoon flies toward the targeted OSD and then releases a platform connected to a boom. Consequently, the spacecraft fires the harpoon toward the center of the platform, resulting in establishing a firm grip of the OSD and in connecting both objects together.[55] The device can also be equipped with a tether to induce a planned landing toward Earth's surface, hence its incineration.[55]

4.3.5. Client-Servicer Deorbiter Technology. Another technology, namely the client-servicer deorbiting technology, involves launching a separate spacecraft equipped with a tug, i.e., a device that has the ability to attach itself magnetically to the target satellite to deorbit it.[55] This technology works by launching a spacecraft composed of a client spacecraft and a servicer spacecraft, in which the client spacecraft detaches itself to take a space tour in search of targeted OSD.[55] It can utilize a tug or docking plates to deorbit the OSD in a graveyard orbit or back to Earth for atmospheric incineration.[55] However, a major difficulty faced with this technology is the fact that newest satellites are planned to be magnetically neutral, making it impossible for this technology to work in the future, though it can still be effective with the current OSD cloud present.[55]

4.3.6. Magnetic Space Tugs. As discussed before, a magnetic space tug works in a contactless manner in order to direct the targeted OSD or spacecraft out of orbit by generating a magnetic field that would either repel or attract the targeted object.[57] This technology can be used to target multiple OSD (defunct satellites) of interest at the same time.[57] A magnetic space tug communicates with a satellite's magnetorquer, i.e., its internally built device that maintains its pull toward Earth to ensure its orbit, with the help of Earth's magnetic field.[57]

4.3.7. Chemical Propulsion for Deorbiting. Chemical propulsion is the process at which the satellite is moved by exothermic chemical reactions in its propulsion system, creating thrust to move it out of the orbit it is located in.[58] This process heavily relies on stored fuel that will initiate the exothermic chemical reaction, i.e., sufficient heat leading to the expansion of the molecules, and hence their forceful escape and thrust provision.[58] A chemical propulsion system consists of the following components: a propellant delivery and storage chamber, turbo-pumps, a combustion chamber, a thrust vector control system, an ejecting nozzle, and exhaust.[59] The propellant delivery chamber ensures that the chemical reactants of the fuel are delivered according to the predetermined reaction conditions.[59] In the reaction chamber, the reactants mix and release the heat required for propulsion in the form of an exothermic reaction, at which the thrust driving the spacecraft for deorbiting expels this heat, as well as gaseous reaction product through the exhaust with the help of the actuators and control systems present in the thrust vector control system.[59]

There are two main types of chemical propulsion: liquid chemical propulsion and solid chemical propulsion. Gaseous/liquid propulsion relies on two main fuels: monopropellant and bipropellant fuels.[58] Another type of propulsion system that combines both liquid and solid propulsion systems is called the hybrid propulsion system.[58] In addition to hybrid, solid, and liquid propulsion fuels, chemical propulsion systems can also utilize nuclear reactions to produce the thrust required for deorbiting. The monopropellant fuel comprises a single type of fuel, whereas the bipropellant comprises an oxidizer along with a fuel.[58] The most common type of fuel for monopropellants is hydrazine or green fuel, i.e., AF-M315E (discussed previously). Depending on their individual chemical properties, bipropellants can either take the form of cryogenic fuels (if their storage requires to be maintained at temperatures below 0 °C), or hypergolic fuels (if the reactants ignite upon getting in contact with one another, without having the need for a reaction chamber).[58]

Despite their high reactivity, toxicity, and ample safety requirements for storage and handling, hypergolic fuels are considered better liquid propellants, as they eliminate the probability of failures due to the ignition process and reaction chamber maintenance. Cryogenic fuels are safer to handle and are also used with nuclear propulsion systems, and the most common cryogenic reactants are liquefied hydrogen and liquefied oxygen. Their disadvantage is that they have stringent storage requirements to keep them at their cryogenic temperatures while they are stored as raw materials for the reaction. Regardless of the type of fuel utilized, chemical propulsion systems generate a huge amount of thrust in a short duration; thus, they are considered highly efficient.[58]

4.3.8. Electrical Propulsion. Electric propulsion systems utilize a gaseous fuel that feeds into one of the following propulsion systems: an electrical field, magnetic field, or electrical heating system. There are three main types of electrical propulsion systems: ion propulsion, hall-effect propulsion, and thermal/resistojet propulsion. When compared with chemical propulsion systems, electrical propulsion systems can consume solar energy in order to deorbit. They are not considered efficient in terms of thrust generation; however, they consume small amounts of fuel over time.[58]

4.3.9. Electrodynamic tethers. This device utilizes an electromagnetic tether, a conductive device that diverts the spacecraft toward Earth's electromagnetic field in order to induce its atmospheric incineration above Earth's surface by generating an electromagnetic force.[55] It can consist of different components out of which one company, known as Amergint Technologies, developed the tether system to include a long conductor tape that is released upon the burning of one or more burn-wires that expel a tether cover, holding masses (i.e., conductor wires) together. These masses are attached to a pretensioned loop connected to a spring, which releases to set them free.[60] The burn-wire heats up and burns through a current that is passed by to release the spring, thus releasing the conductor tape.[55,60] Consequently, this tape ensures that the satellite is directed toward Earth's electromagnetic field.[55]

4.3.10. Using Robotic Arms to Capture Defunct Satellites. This technology involves the utilization of multiple robotic arms to grasp into an OSD and drag it toward Earth or toward the disposal orbit for deorbiting.[55] It is noted that this technology does not capture multiple OSD pieces, and studies are in progress.[55]

4.3.11. Laser. This technology utilizes radiation pressure emitted from a laser light, under the vacuum conditions of space, in order to push the OSD of interest out of its current orbit, and it could also be used to direct the object toward Earth in a contactless manner, at which it will be subject to atmospheric incineration.[61]

Several factors need to be considered and preset before directing the laser toward the OSD of interest in order to avoid expanding the OSD cloud further upon burning the object into ample smaller OSD pieces, and these factors include the laser's firing duration, intensity, polarization, and aim.[61] It has been determined that prior to firing the laser beam, the orbit of the OSD must be determined and the surroundings must be analyzed to ensure that the laser beam does not interfere with any other satellites on track.[61] Furthermore, the OSD's new orbital track and its direction need to be determined. Consequently, telescopes on Earth can be used to monitor and track the OSD to ensure its landing toward Earth's surface and its atmospheric incineration. Although the technology is promising, it has been reported that as the dimensions of the OSD vary, the technique of firing the laser beam needs to be customized per OSD encountered.[61] Another disadvantage of using this technology is that upon the occurrence of an error with the process, the OSD of target can become nontrackable, especially if the deorbit location was not Earth or graveyard orbits, since it can be pushed at a certain speed that enables distancing it further.[61]

4.3.12. Long-Term Servicing of Current Satellites. Another solution to reduce the amount of OSD to be formed is by firing a spacecraft in order to perform servicing operations that will elongate the life of the targeted satellite.[15] These operations can include maintenance for damaged satellites or refueling satellites that are left in orbit after running out of fuel.[15] This technology is currently being applied on the ISS to preserve it. Although this solution is reasonable and effective, it does not have the ability to treat or eliminate OSD pieces that are present in huge quantities and are scattered throughout LEO and GEO orbits as most of the OSD pieces are made of broken satellite equipment that cannot be fueled or fixed to deorbit.

5. UPCOMING MISSIONS

There are several upcoming missions that might affect the amount of the currently present amount of OSD, and some of these missions are expected to take place as follows:

- China discovered helium-3 content within a lunar mineral that has been named as Changesite-Y and is planning on conducting three unmanned trips to the moon to extract the potential green energy source, i.e., an environmentally friendly energy source with no known emissions.[62]
- Japan plans to construct and place a direct lift to space near the ISS at a distance of nearly 400 km above sea level by 2050, and the construction is expected to begin in 2025.[63] The lift will connect Earth with space through a 96 000 km cable and carbon nanotubes and is set to carry people and objects, making the flight affordable and available to the public. It is estimated that it will rely on solar energy only to power up the lift, and it is expected to transmit microwave energy from the sun to Earth as a green source of energy.[63]
- Rotating space hotels, having their construction starting from the year 2026, are planned by several companies.[64]
- Virgin Galactic Spaceship Company officially announced that they have plans to conduct 400 flights each year, which can be open to the general public.[35]
- Blue Origin is planning on facilitating an 11 min journey from Earth to 62 mi above Earth's surface, i.e., above the Karman line.[64]
- SpaceX is working on implementing a 30 min flight across space, carrying up to seven passengers from Earth to space.[6,65]
- Actor Tom Cruise is expected to be the first person to shoot a movie in space at the ISS in December 2024.[66] This will open the doors for more movies to be shot in space, upon its success.

Since the number of low earth orbit satellites is projected to increase, with perhaps 50 000 additional satellites in the orbit by 2030, environmental and other effects due to space activity need to be considered more seriously.[63]

6. CONCLUSION

Even without upcoming space tourism flights, rotary space hotel construction missions, and moon mineral extraction for green energy, the current volume of orbital space debris (OSD) is alarming in terms of collision risks due to its massive size. This Review provides a summary on how OSD is generated not only in the form of tracked and untracked OSD fragments but also in the form of spacecraft exhaust atmospheric emissions that either act as OSD particles due to their large size or as O_3 decomposers and global warming contributors. This work outlines details of mitigation technologies and pollution prevention techniques to reduce the OSD cloud and to enhance spacecraft shielding to reduce the risk of debris creation. Moreover, green fuel alternatives are discussed to launch spacecraft with negligible air pollutant emissions, which will hence slow the degradation of the ozone layer and have a probable positive impact on the climate. This Review also calls for OSD mitigation measures that can replace the eventual OSD incineration or graveyard disposal of OSD, solely to minimize the release of pollutants in the atmosphere and hence decrease the global warming effect.

■ AUTHOR INFORMATION

Corresponding Author

Zarook Shareefdeen − *Department of Chemical and Biological Engineering, American University of Sharjah, Sharjah, United Arab Emirates;* orcid.org/0000-0001-5051-2504; Email: zshareefdeen@aus.edu

Author

Hadeel Al-Najjar − *Department of Chemical and Biological Engineering, American University of Sharjah, Sharjah, United Arab Emirates*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c06887

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The work in this paper was supported, in part, by the Open Access Program from the American University of Sharjah. This paper represents the opinions of the author(s) and does not mean to represent the position or opinions of the American University of Sharjah. This research received no external funding.

■ REFERENCES

(1) ESA Space Debris Office. *Space Debris by the Numbers*; European Space Agency, 2023https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers (accessed 2023-03-10).

(2) Dooling, D. Columbia disaster. *Encyclopedia Britannica*; Encyclopædia Britannica, Inc., January 25, 2023. https://www.britannica.com/event/Columbia-disaster (accessed 2023-02-13).

(3) Uri, J. 50 years ago: Remembering the crew of Soyuz 11. National Aeronautics and Space Administration, June 30, 2021. https://www.nasa.gov/history/50-years-ago-remembering-the-crew-of-soyuz-11/.

(4) Wall, M. Russian Space Cargo Ship Crash Blamed on Soyuz Rocket. Space.com, May 15, 2015. https://www.space.com/29411-russian-cargo-spaceship-crash-soyuz-rocket.html (accessed 2023-10-08).

(5) National Aeronautics and Space Administration. *Orbital Debris Q. News* **2023**, *27* (3), 1−14.

(6) Miraux, L. Environmental limits to the space sector's growth. *Science of The Total Environment* **2022**, *806*, 150862.

(7) Lambert, J. (2018, September). Fengyun-1C debris cloud evolution over one decade. In *Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference*, Waileau, Hawaii, September 11−14, 2018; Ryan, S. , Ed.; Maui Economic Development Board, Inc.: Kihei, Hawaii, 2018. https://ui.adsabs.harvard.edu/abs/2018amos.confE..50L/abstract (accessed 2023-02-13).

(8) *Previous nuclear incidents and accidents: COSMOS 954*; Health Canada: Ottawa, Ontario, 2019. Retrieved February 13, 2023, from https://www.canada.ca/en/health-canada/services/health-risks-safety/radiation/radiological-nuclear-emergencies/previous-incidents-accidents/cosmos-954.html (accessed 2023-02-13).

(9) Clark, S. Breaking news: Near-misses between space station and debris on the rise. *Spaceflight Now*; Spaceflight Now, Inc., April 5, 2012.https://spaceflightnow.com/news/n1204/05spacedebris/ (accessed 2023-02-13).

(10) UK Parliamentary Office of Science and Technology. Impacts on Earth from Space. *POST*, 1996; note 80. https://www.parliament.uk/globalassets/documents/post/pn080.pdf (accessed 2022-10-17).

(11) Hobbs, S.; Stansbery, G.; de Carvalho, T. Space Waste. *Waste* **2019**, 567−583.

(12) Gallag, K. Major Components of a Satellite. *Show Me the Physics*, 1997. https://www.showmethephysics.com/97/KGALLAG.HTM (accessed 2022-07-24).

(13) Sterling, M. The Role of Machined Components in Satellite Communications | Ardel. *Ardel Engineering*, June 30, 2021. https://www.ardelengineering.com/blog/machined-components-in-satellite-communications (accessed 2022-07-01).

(14) NASA Stem Team. What Is a Satellite?. *NASA*, February 8, 2017. https://www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-is-a-satellite-k4.html (accessed 2022-07-07).

(15) Howell, E.; Biggs, B. What is a satellite? *Space.com*, January 17, 2022. https://www.space.com/24839-satellites.html (accessed 2023-02-13).

(16) Cook, W. The Anatomy of a Satellite. *William Craig Cook*, 1996. http://www.williamcraigcook.com/satellite/anatomy.html (accessed 2022-07-20).

(17) Parts of a satellite. *RF Wireless World*, n.d. https://www.rfwireless-world.com/Tutorials/parts-of-satellite.html (accessed 2022-07-17).

(18) Parts of a satellite. *Science Learning Hub*, March 27, 2013.https://www.sciencelearn.org.nz/videos/123-parts-of-a-satellite (accessed 2022-07-01).

(19) Hart, D. Satellite Communications. *Washington University in St. Louis*, 1997. https://www.cse.wustl.edu/~jain/cis788-97/ftp/satellite_nets/index.html (accessed 2022-02-05).

(20) Satellite Basics. *Intelsat*, n.d. https://www.intelsat.com/resources/tools/satellite-101/ (accessed 2022-06-13).

(21) Space Foundation Editorial Team Components of a Satellite. *Space Foundation*, n.d.https://www.spacefoundation.org/space_brief/satellite-components/ (accessed 2022-06-22).

(22) What is Satellite? https://informationq.com/satellite-overview/ (accessed 2022-06-12).

(23) Hydrazine. *PubChem*; National Library of Medicine: Bethesda, MD, n.d.https://pubchem.ncbi.nlm.nih.gov/compound/Hydrazine (accessed 2022-11-23).

(24) Sforza, P. M. Nuclear rockets. *Theory of Aerospace Propulsion* **2012**, 517−540.

(25) The History of Nuclear Power in Space. *Energy.gov*, June 9, 2015. https://www.energy.gov/articles/history-nuclear-power-space.

(26) Nuclear Electric Propulsion History Part 1: The Soviet Astronuclear Program. *Beyond NERVA*, November 8, 2018. https://beyondnerva.com/2018/11/08/nuclear-electric-propulsion-history-part-1-the-soviet-astronuclear-program/.

(27) Johnson, N. L. A New Look at Nuclear Power Sources and Space Debris. In *Proceedings of the 4th European Conference on Space Debris (ESA SP-587)*, Darmstadt, Germany, April 18−20, 2005; Danesy, D., Ed.; European Space Agency, 2005; p 551.

(28) Kirvan, P. Definition: uplink and downlink. *TechTarget*, n.d https://www.techtarget.com/searchmobilecomputing/definition/downlink-and-uplink (accessed 2022-06-13).

(29) Dellaporta, J. What Is a Transponder?. *EasyTechJunkie*, n.d.https://www.easytechjunkie.com/what-is-a-transponder.htm (accessed 2022-06-15).

(30) Types of orbits. *The European Space Agency*, March 30, 2020. https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits (accessed 2022-12-22).

(31) Beginner's Guide to Propulsion. *National Aeronautics and Space Administration*, n.d., updated May 13, 2021. https://www.grc.nasa.gov/www/k-12/airplane/bgp.html (accessed 2023-01-19).

(32) Thrust Equation. *National Aeronautics and Space Administration*, n.d., updated July 27, 2022. https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/thrust-force/ (accessed 2023-01-19).

(33) Combustion.*National Aeronautics and Space Administration*, n.d., updated May 13, 2021. https://www.grc.nasa.gov/www/k-12/airplane/combst1.html#:~:text=As%20a%20result%20of%20combustion,or%20the%20source%20of%20heathttps://www.grc.nasa.gov/www/k-12/airplane/combst1.html#:~:text=As%20a%20result%20of%20combustion,or%20the%20source%20of%20heat (accessed 2023-01-19).

(34) Scientific Organizing Committee; Dark Sky Oases Working Group; Optical Astronomy Working Group; Bioenvironment Working Group; Satellite Constellation Working Group, Radio Astronomy Working Group; 2020; *Dark and Quiet Skies for Science and Society: Report and recommendations*; United Nations Office for Outer Space Affairs: Vienna, Austria, 2021https://www.iau.org/static/publications/dqskies-book-29-12-20.pdf.

(35) Ryan, R. G.; Marais, E. A.; Balhatchet, C. J.; Eastham, S. D. Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate. *Earth's Future* **2022**, *10* (6), e2021EF002612.

(36) Federal Communications Commission. Mitigation of Orbital Debris in the New Space Age. *Federal Register* February 19, 2019, *47*, 4742−4757. https://www.federalregister.gov/documents/2019/02/19/2019-02230/mitigation-of-orbital-debris-in-the-new-space-age (accessed 2022-10-26).

(37) Finlayson-Pitts, B. J.; Pitts, J. N. Rates and mechanisms of gas-phase reactions in irradiated organic − nox − air mixtures. *Chemistry of the Upper and Lower Atmosphere* **2000**, 179−263.

(38) Adushkin, V.; Aksenov, O.; Veniaminov, S.; Kozlov, S.; Tyurenkova, V. The small orbital debris population and its impact on space activities and ecological safety. *Acta Astronautica* **2020**, *176*, 591−597.

(39) Fleming, D. (2016, June 9). Properties of alloys: Finding the NaK. *Royal Society of Chemistry*, June 9, 2016. https://edu.rsc.org/exhibition-chemistry/properties-of-alloys-finding-the-nak/2000056.article (accessed 2023-01-08).

(40) Shareefdeen, Z.; Al-Najjar, H. Gaseous and Solid Waste Management in Waste-to-Energy Processes. In *Hazardous Waste Management: Advances in Chemical and Industrial Waste Treatment and Technologies*; Shareefdeen, Z., Ed.; Springer, 2022; p 233−255.

(41) Polar Stratospheric Clouds. *Equitable Client Dynamics*, n.d https://groups.seas.harvard.edu/climate/eli/research/equable/psc.html (accessed 2023-01-08).

(42) Chandler, D. L. Explained: Radiative forcing. *MIT News*, March 10, 2010.https://news.mit.edu/2010/explained-radforce-0309 (accessed 2023-08-01).

(43) Where do old satellites go when they die?. *Space Place*, n.d., updated October 31, 2022. https://spaceplace.nasa.gov/spacecraft-graveyard/en/ (accessed 2022-11-10).

(44) Pultarova, T. Air pollution from reentering megaconstellation satellites could cause ozone hole 2.0. *Space.com*, June 7, 2021. https://www.space.com/starlink-satellite-reentry-ozone-depletion-atmosphere (accessed 2022-11-10).

(45) Murphy, D. M.; Abou-Ghanem, M.; Cziczo, D. J.; Froyd, K. D.; Jacquot, J.; Lawler, M. J.; Maloney, C.; Plane, J. M. C.; Ross, M. N.; Schill, G. P.; Shen, X. Metals from spacecraft reentry in stratospheric aerosol particles. *Proc. Natl. Acad. Sci. U.S.A.* **2023**, *120* (43), No. e2313374120.

(46) International Organization for Standardization. *Space systems: Space debris mitigation requirements*; ISO 24113:2019; Geneva,

Switzerland, 2019. https://www.iso.org/standard/72383.html (accessed 2023-02-08).

(47) Goguichvili, S.; Linenberger, A.; Gillette, A.; Novak, A. The Global Legal Landscape of Space: Who writes the rules on the final frontier? *Wilson Center*, October 1, 2021. https://www.wilsoncenter.org/article/global-legal-landscape-space-who-writes-rules-final-frontier (accessed 2023-02-08).

(48) Oberhaus, D. A New Fuel for Satellites Is So Safe It Won't Blow Up Humans. *Wired*, June 12, 2019. https://www.wired.com/story/a-new-fuel-for-satellites-is-so-safe-it-wont-blow-up-humans/ (accessed 2022-10-18).

(49) Masse, R. K.; Allen, M.; Driscoll et al. AF-M315E Propulsion System Advances & Improvements. In *Proceedings of the AIAA/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, UT, July 25−27, 2016; American Institute of Aeronautics and Astronautics: Reston, VA, 2016. https://ntrs.nasa.gov/api/citations/20170001286/downloads/20170001286.pdf (accessed 2023-02-07).

(50) Advanced Spacecraft Energetic Non-Toxic Propellant. *Air Force Research Laboratory*, n.d. https://afresearchlab.com/technology/aerospace/successstories/advanced-spacecraft-energetic-non-toxic-ascent-propellant/ (accessed 2023-02-08).

(51) International Space Station Facts and Figures. *National Aeronautics and Space Administration*, n.d. https://www.nasa.gov/feature/facts-and-figures (accessed 2022-01-16).

(52) Martinez, S. L. Analysis of Leo Radiation Environment and Its Effects On Spacecraft's Critical Electronic Devices. Master's Thesis, Embry-Riddle Aeronautical University, Daytona Beach, FL, 2011.

(53) Outgassing test facility brings new materials into space industry. *National Aeronautics and Space Administration*, 2017. https://spinoff.nasa.gov/Spinoff2017/ip_8.html (accessed 2023-01-25).

(54) Qi, H.; Shi, Q.; Qian, Y.; Li, Y.; Xu, J.; Xu, C.; Zhang, Z.; Xie, X. The atomic oxygen erosion resistance effect and mechanism of the Perhydropolysilazane-derived SiOx coating used on polymeric materials in Space Environment. *Polymers* **2022**, *14* (2), 322.

(55) Caldwell, S. Deorbit systems. In *State-of-the-Art of Small Spacecraft Technology*. National Aeronautics and Space Administration: Washington, D.C., 2021. https://www.nasa.gov/smallsat-institute/sst-soa/deorbit-systems (accessed 2023-02-10).

(56) Barato, F. Comparison between different re-entry technologies for debris mitigation in leo. *Applied Sciences* **2022**, *12* (19), 9961.

(57) Magnetic Space Tug Could Target Dead Satellites. *The European Space Agency*, June 19, 2017. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Magnetic_space_tug_could_target_dead_satellites (accessed 2023-02-13).

(58) Chemical Propulsion Systems. *Glenn Research Center*, n.d. https://www1.grc.nasa.gov/research-and-engineering/chemical-propulsion-systems/ (accessed 2023-02-13).

(59) Components of a Chemical Propulsion System. *Glenn Research Center*, n.d. https://www1.grc.nasa.gov/research-and-engineering/chemical-propulsion-systems/components/ (accessed 2023-02-13).

(60) Thurn, A. Burn wire release mechanism for spacecraft and Terrestrial Applications. US 10351269 B2.https://patents.google.com/patent/US10351269B2/en (accessed 2023-02-11).

(61) Peltoniemi, J. Dangerous space debris to be removed with laser. *National Land Survey of Finland*, March 17, 2020. https://www.maanmittauslaitos.fi/en/topical_issues/dangerous-space-debris-be-removed-laser (accessed 2023-02-13).

(62) Mann, J. China plans three missions to the Moon after discovering a new lunar mineral that may be a future energy source. *Business Insider*, September 12, 2022. https://www.businessinsider.in/science/space/news/china-plans-three-missions-to-the-moon-after-discovering-a-new-lunar-mineral-that-may-be-a-future-energy-source/articleshow/94132717.cms (accessed 2023-02-13).

(63) Salam Groovy Japan Staff. Japan's 'space elevator' ready to build in 2025. *Salam Groovy Japan*, November 5, 2021. https://www.groovyjapan.com/en/space-elevator/ (accessed 2023-02-13).

(64) Guarino, B. How to travel to space, Earth's hottest new destination. *The Washington Post*, January 9, 2023. https://www.washingtonpost.com/travel/2023/01/09/space-tourism-travel/ (accessed 2023-02-09).

(65) Earth orbit. SpaceX, 2022. https://www.spacex.com/humanspaceflight/earth/ (accessed 2023-02-13).

(66) Shoard, C. Film studio in space planned for 2024. *The Guardian*, January 20, 2022. https://www.theguardian.com/film/2022/jan/20/film-studio-in-space-planned-for-2024 (accessed 2023-02-08).