

UDC 504.06:631.41:662.75

<https://doi.org/10.31073/ecobezpeka202507-11>

IMPACT OF SPACE LAUNCHES ON THE ENVIRONMENT

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In the past, the environmental impact of the space industry has been overlooked. The main reason for this is the small number of large rocket launches per year. But today, the dynamics of growth in the number of launches is impressive - from 114 in 2018 to 222 space launch attempts (211 of which were successful) in 2023. The aim of the study is to assess the impact of space launches on the environment. Each launch of a large rocket brings not only great benefits, both scientific and practical, but also a significant amount of emissions. At the same time, different types of rockets have different environmental impacts. In addition to the impact of spent rocket stages and debris falling into remote areas, oceans, or densely populated areas, there is a negative impact on the atmosphere. All rockets use fossil fuels and emit carbon dioxide and water. But some types of engines are more environmentally acceptable than others. Current research shows that kerosene-fueled rockets and some types of hybrid engines emit significant amounts of black carbon. At the same time, the amount of black carbon emitted by such rockets is already comparable to the amount of soot emitted by the entire aviation industry. Rocket fuel residues contain toxic compounds that have a negative impact on the environment. Therefore, the development of environmentally friendly fuels, such as methane or hydrogen, is becoming increasingly important. Another type of impact on the atmosphere is the destruction of the ozone layer. High temperatures during rocket flight lead to the formation of large amounts of nitrogen oxides, which can destroy ozone in the stratosphere. The destruction of the ozone layer is a global environmental problem with serious consequences for the environment. The current state of the industry does not have a large-scale impact on climate change. However, looking to the future, the dynamics of the growth in the number of launches indicates the need for environmental regulation.

Keywords: Environment, ozone layer, emissions, air pollution, rocket engine

Problem statement

The space industry is one of the fastest growing industries in the world today. Revenue from this industry is projected to grow from \$350 billion in 2019 to over \$1 trillion and is expected to reach \$2.7 trillion by 2045 [18].

This huge demand is due to many factors: lower launch costs due to commercialization, increasing dependence on satellite technology for GPS, surveillance, and broadband internet. The issue of the militarization of space remains open. In this regard, new space launch and rocket production centers are emerging around the world. In addition, 2021 can be considered the beginning of commercial spaceflight and space tourism [5]. Thus, the space industry is growing rapidly, but it also has a significant impact on the environment.

As the number of rocket launches grows annually, there is a need to adapt the regulatory system as the industry is subject to change. An increase in the number of launches can lead to an increase in negative environmental impact, in particular, even a small increase in the number of launches compared to current levels can have serious environmental consequences [6]. At the same time, the CEO of SpaceX said that the ultimate goal of Starship development is to launch up to three times a day, which is equivalent to about 1000 flights a year. Therefore, regulatory authorities should anticipate the negative consequences of such a number of launches and take appropriate action. The purpose of our work is an analysis of the assessment of the possible negative impact of space launches on the environment.

Analysis of the latest research and publications

Space rocket launches have a significant impact on the environment in several key ways:

During rocket launches, various chemicals are released into the atmosphere, including aluminum oxide, hydrogen chloride, soot, and other compounds, depending on the type of fuel. These emissions can cause acid rain, increase the concentration of suspended particles in the air, and change weather conditions in the areas surrounding the launch sites. Particularly dangerous are soot emissions in the upper atmosphere, as they can persist for several years and have a significant greenhouse effect that is hundreds of times greater than the impact of similar emissions on the earth's surface.

Some combustion products of rocket fuel, such as nitrogen oxides and chlorine, can interact with the ozone layer, causing its destruction. This increases the level of ultraviolet radiation reaching the Earth's surface and can negatively affect human health and ecosystems.

In the areas where separating parts of missiles fall, soil contamination with rocket fuel residues and structural fragments is observed. This can lead to the accumulation of toxic substances in the soil, which can be absorbed by plants and, ultimately, by animals and humans. In addition, mechanical contamination by solid fragments can reduce crop yields [2].

Rocket fragments and inoperable satellites left in orbit create space debris that poses a threat to existing spacecraft and future missions. With the increasing number of launches, this problem is becoming more and more urgent. As of 2023, there are more than 23,000 objects of space debris larger than a softball in Earth's orbit, as well as more than 100 trillion untraceable smaller particles.

The use of nuclear power sources on spacecraft carries the risk of radioactive contamination in the event of accidents or uncontrolled reentry of such vehicles to Earth. This can cause significant damage to both the environment and human health [3].

The growing intensity of space activities requires the development and implementation of international standards and measures aimed at minimizing the negative impact on the environment. This includes the use of environmentally friendly fuels, the development of technologies to reduce

space debris, and effective management of the life cycle of spacecraft. It is also necessary to systematically monitor and assess environmental risks associated with space activities to ensure sustainable development and environmental protection.

Analysis of the latest research and publications

A thorough analysis of scientific articles, technical reports and reviews covering the impact of various types of rocket fuel on the atmosphere, soil, water resources and the ozone layer was conducted. The main focus was on research on pollutant emissions, mechanisms of ozone depletion, and accumulation of toxic substances in soil and water. The sources used include the works of the authors [1, 2, 7, 8, 11, 16, 17].

The types of rocket fuel were systematized and classified, including solid, liquid, hybrid, and hydrogen. Each type of fuel was evaluated in terms of its chemical

To quantify the impact of launches, data on the number of launches in 2019 and associated emissions (H_2O , CO_2 , NO_x , Al_2O_3 , Cl_2) were used. The modeling results obtained from previous studies [15,12], made it possible to assess how emissions from launches affect the ozone layer and global climate.

The impact of chemical fuel residues and mechanical debris in the areas where rocket parts fall on soils and water bodies was analyzed. Particular attention is paid to spaceports in Kazakhstan, the United States, French Guiana, and other regions with high launch activity.

An analysis of the amount of space debris generated over the period 1957-2019 was carried out. The data was obtained from international databases and compared between the leading countries in terms of the number of launches [17].

Best practices and strategies for reducing the environmental impact of rocket launches, including the use of «green» hydrogen, the development of biofuels.

Determining the goals of the article (task statement)

The aim of the study is to assess the environmental impact of space launches.

Summary of the main research material

In just 40 years, rocket and space activities have created serious problems by polluting the earth's surface, atmosphere, and near-Earth space [17]. In this regard, it becomes extremely important to objectively assess all areas of negative impact of rocket and space activities.

The first obvious pollutant is space debris. Table 1 shows the countries that have been most active in space activities. Between 1957 and 2019, 5912 launches were carried out. The most active suppliers of space debris are Russia, the United States, and China, which account for 90.5% of all space debris [17].

Another environmental impact factor is emissions from rocket engines. Although modern engines

Table 1

Amount of space debris for the period from 1957 to 2019 by country

№	Countries, regions	Number of polluting objects space
1	Russia	6075
2	USA	4867
3	China	3623
4	Europe	367
5	India	174
6	Japan	183
7	Other countries	605
Total:		16094

Table 2

Types of rocket engines in use today

Engine type	Fuel	Advantages	Disadvantages
Liquid rocket engines	Liquid fuel (hydrogen, oxygen, kerosene, liquid nitrogen) and oxidizer	High traction, high efficiency, possibility of adjustment of traction	Complexity, high cost
Solid rocket engines	Solid fuel (based on polyurethane or nitrocellulose)	Simplicity, reliability, low cost	Low traction, inability to adjust traction
Hybrid rocket engines	Liquid fuel and solid oxidizer	Combines the advantages of RRD and TRTD: high traction, reliability, adjustable traction	Complexity, high cost
Nuclear rocket engines	Nuclear fuel (uranium rod)	Potentially the highest thrust, the ability to fly long distances	Very difficult, expensive, dangerous, ethical issues

are capable of operating with high efficiency in converting fuel energy into thrust, they are extremely inefficient from an environmental point of view [9]. Toxic rocket fuel has a catastrophic impact on the environment. It pollutes the upper atmosphere, where the accumulation of combustion by-products leads to the loss of the ozone layer [3]. Table 2 shows the different types of engines in use today.

Most of the air pollution comes from the propellant and oxidizer used in the various stages of a rocket launch. The four main classes of rocket fuel that are most commonly used include kerosene, hyperbolic fuel, liquid hydrogen (cryogenic), and solid fuel [14]. The combustion of these fuels releases various pollutants into the atmosphere, such as water vapor, nitrogen oxides, black carbon, and particulate matter. It is important to note that these pollutants also contribute to the depletion of the ozone layer through gas-phase reactions or activation of chlorine in the atmosphere [13].

Figure 1 shows the locations of all 127 documented rocket launches in 2019, dominated by China (34 launches), Kazakhstan (22), Russia (22), and US-led launches in the United States (21) and New Zealand (6).

Others include launches by the European Space Agency (ESA) from French Guiana (9), Iran (5), and launches in India (6) and Japan (2) by their respective space agencies. Shares by weight of the four main fuels (kerosene, hypergolic, liquid hydrogen, and solid propellants) used in each country [15].

Solid propellants dominate launches from Japan, India, and French Guiana. Hypergolic fuels are typical for China, Kazakhstan, and Iran. Kerosene is the dominant fuel for launches in New Zealand, Russia, and the United States. The total amount of rocket fuel used in 2019 was 32 Gg and included 45% kerosene, 32% hypergolic, 14% solid and 8% liquid hydrogen [10].

Figure 2 shows the mass of each pollutant emitted in 2019 within the model's altitude range. This includes the combustion of fuel in the booster and first stage of the rocket, as well as from re-entry heating. The relative mass of each emitted component is the same for each month. Emissions from the booster and first stage of the rocket, which occur within the altitude limits of GEOS-Chem, account for the majority of total emissions from all stages: 80% for NO_x, 94% for Al₂O₃ and HCl + Cl, 84% for H₂O and

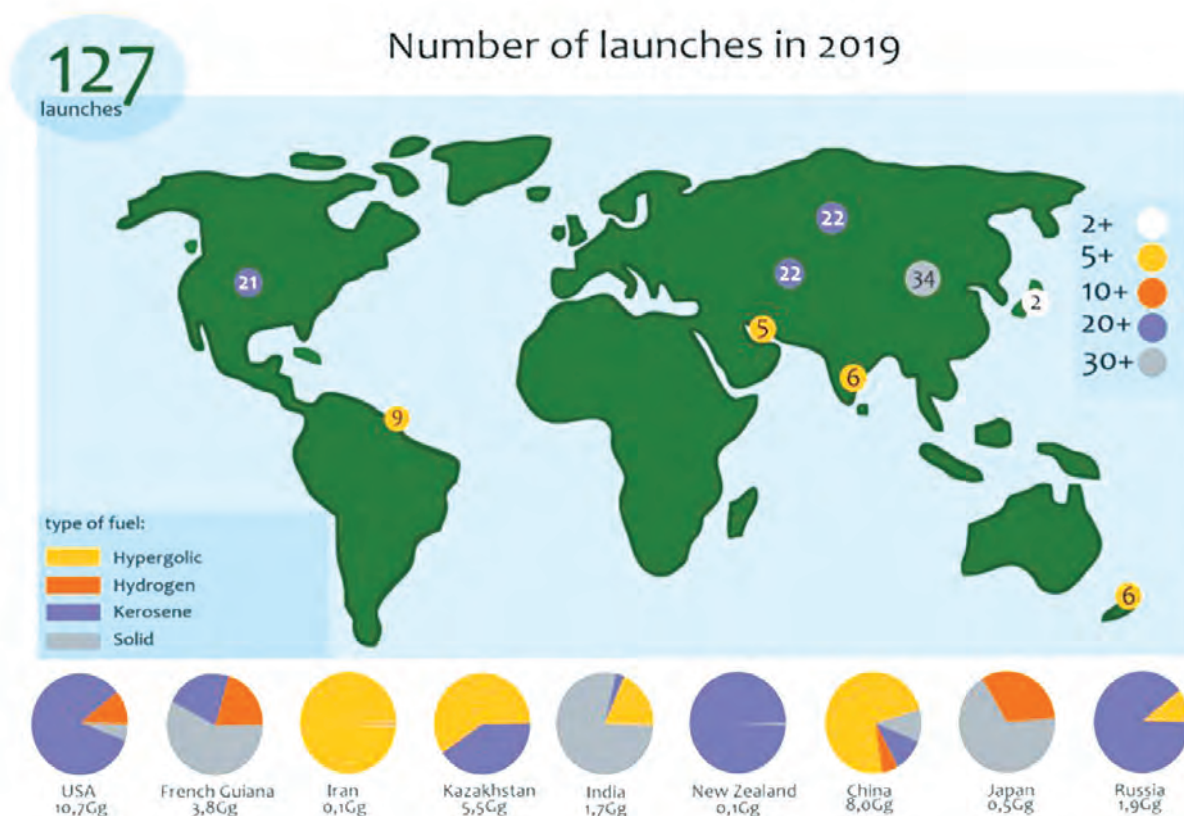


Figure 1. Locations of rocket launches in 2019 and pie charts.

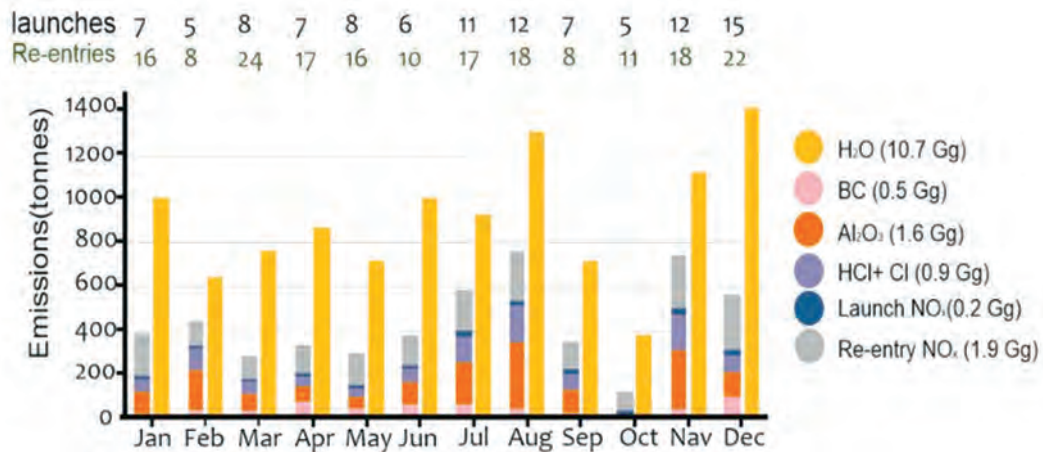


Figure 2. Mass of pollutants emitted in 2019 in the world

79% for BC. The amount of emissions above 15 km is 78%-79% for H₂O and BC, and 68%-69% for Cl and Al₂O₃ [12].

Different types of fuels have different environmental impacts, depending on their chemical composition and combustion processes.

Solid propellants, which are commonly used in rockets, have a significant negative impact on the environment. Its combustion is accompanied by emissions of greenhouse gases such as CO₂ and particulate matter, and emissions of nitrogen oxides (NO_x) and chlorine oxides (HCl) contribute to the destruction of the ozone layer and the formation of acid rain [7].

Liquid fuels, such as kerosene, jet fuel, or liquid hydrogen, have a lower environmental impact. It produces fewer greenhouse gases than solid fuels, but it can still pollute the atmosphere with particulate matter. There is also a risk of liquid fuel leakage, which can lead to serious soil and water pollution [1].

Hybrid fuels, which combine elements of solid and liquid fuels, have a lower environmental impact because they produce fewer greenhouse gases and particulate matter. However, chemical washout from rocket launch sites, noise, and debris from launches can still have a negative impact on the environment [8].

Hydrogen is considered to be one of the most environmentally friendly rocket fuels because it does not generate greenhouse gases during combustion. However, hydrogen production can have a negative impact on the environment, depending on the method used. Speaking of green hydrogen, it is the only type of fuel that has an environmental perspective [16].

While solid propellants are efficient for certain

types of rockets due to their stability and high energy density, their combustion significantly contributes to environmental degradation. Besides the direct emission of greenhouse gases (GHG) such as CO₂, the particulate matter released during combustion can contribute to air pollution and climate change. Nitrogen oxides (NO_x) and chlorine-based compounds like HCl from solid propellants are particularly damaging to the ozone layer, accelerating its depletion. The accumulation of these pollutants can also lead to regional ecological disturbances, including acidification of soils and water bodies.

Liquid fuels, including kerosene and liquid hydrogen, are widely used due to their relatively lower GHG emissions compared to solid fuels. However, the environmental risks associated with liquid fuels primarily stem from their handling and storage. Leakage of these fuels into the environment can lead to soil contamination and water pollution, severely impacting local ecosystems. For instance, kerosene spillages can destroy vegetation and aquatic life due to its toxicity. Moreover, while liquid hydrogen combustion produces water vapor, its production process, often reliant on fossil fuels, can result in significant GHG emissions unless green hydrogen methods are employed. Hybrid rocket fuels, which utilize a combination of solid and liquid components, represent a middle ground in terms of environmental impact. These fuels offer reduced GHG emissions compared to solid fuels and generate less particulate matter. Despite this advantage, the environmental consequences of hybrid fuel usage are not entirely negligible. Noise pollution from launches, chemical runoff from fueling stations, and debris from rocket

components can disrupt local biodiversity and ecosystems near launch sites [9].

Hydrogen, especially green hydrogen derived from renewable energy sources, holds great promise as a sustainable rocket fuel. During combustion, hydrogen produces only water vapor, making it a clean alternative to traditional fuels. However, the environmental footprint of hydrogen depends heavily on its production method.

Conventional hydrogen production through steam methane reforming generates considerable CO₂ emissions unless carbon capture technologies are employed. On the other hand, green hydrogen, produced through electrolysis powered by renewable energy, offers a truly sustainable and environmentally friendly option. Nonetheless, challenges such as storage, transportation, and the high cost of production need to be addressed for broader adoption in the aerospace industry.

Regardless of the type of fuel used, space launches have several secondary environmental impacts. These include: the intense heat generated during launches can damage nearby vegetation and soil, while shock waves can disrupt wildlife and ecosystems; residual fuels and oxidizers can contaminate soil and water around launch sites; the proliferation of space debris from launches poses a long-term challenge, not only for future space missions but also for atmospheric re-entry, which can release toxic substances; rocket launches generate extreme levels of noise, which can disrupt human and animal populations in the vicinity.

Future Directions to mitigate the environmental impacts of rocket launches, research and development efforts are focusing on: developing cleaner fuels, such as bio-derived rocket fuels or advanced forms of green hydrogen; improving the efficiency of rocket engines to minimize fuel consumption and emissions; implementing stricter environmental regulations for rocket manufacturing, fuel production, and launch site management; investing in technologies to capture and neutralize emissions at launch sites; designing reusable rockets to reduce waste and debris associated with single-use components.

The transition toward more sustainable space exploration practices is critical to balancing humanity's scientific ambitions with the responsibility to protect Earth's environment.

Destruction of the ozone layer and its connection with the flight of large rockets. The Earth's ozone

layer, located in the stratosphere, protects us from the sun's harmful ultraviolet (UV) radiation. This layer consists of ozone (O₃), which is destroyed by active catalysts such as nitrogen oxides (NO_x), chlorine oxides (Cl_x), bromine oxides (Br_x), and hydroxyl radicals (OH) [11]. The exhaust gases from rocket launches, regardless of the type of fuel (Fig. 2), contain NO_x, OH and H₂O, which also destroy ozone. Ozone loss can be localized, within the exhaust plume, or global, reducing the ozone concentration in the entire ozone layer [17].

In general, the impact of different catalysts on ozone depletion can be distinguished. NO_x: Catalytically destroys ozone molecules in the stratosphere. Sources: launch vehicles (mainly Russian and Chinese), airplanes (UDMH/N₂O₄). Impact: 10 Proton launches: 0.00012% annual ozone reduction. Actual losses (2000-2009): 0,00016%. Largest contributors: Russian and Chinese missiles. Contribution of the US Air Force: insignificant (0.0000005%) [2].

Cl_x: Catalytically destroy ozone molecules in the stratosphere. Sources: Solid rocket engines (mostly perchlorate-based). Impact: 816 tons of Cl_x annually: 0.052% of annual ozone decrease at 60°N, 0.017% at 30°N. Actual losses (over 20 years): 0.14%. Largest contributor: US missiles (23.5% over 20 years). Contribution of the US Air Force after 2003: 5,4%. Future projections: 0.0004(3) % annual ozone decrease [1]. Al₂O₃: Photochemical process: Al₂O₃ reacts with chlorine to form Cl_x. Sources: Solid rocket engines. Impact: 1120 tons of Al₂O₃ annually: 0.004% annual ozone depletion. Actual losses (over 10 years): 0.004%. Contribution of the US Air Force: 0,0005% (2006-2008) [14]. H₂O: Negligible impact, indirectly through NO_x. Sources: launch vehicles (mainly Proton). Impact: 628 tons of H₂O annually: 0.00001% annual ozone reduction. Although the impact of some substances, such as H₂O, may be negligible, the overall impact of rocket launches on the ozone layer needs to be carefully studied and monitored. [2].

Conclusions and prospects for further research. Space exploration has become a milestone in human history, providing access to satellite maps, television, and other technologies that are now an integral part of our lives. However, the development of the space industry has significant environmental consequences that require immediate attention. Every space launch

is accompanied by emissions of pollutants that have a negative impact on the environment, including ozone depletion, climate change, acid rain, and an increase in space debris.

Research shows that the growing number of space launches increases emissions of black carbon, nitrogen oxides, water vapor, and other pollutants that contribute to ozone depletion and global climate change. Particularly dangerous are solid fuel and kerosene rockets, which produce high levels of pollution and have a significant impact on the environment. In addition, the accumulation of space debris poses additional risks to the Earth's ecosystem and the functioning of spacecraft.

Ozone depletion and climate change pose a serious threat to human life on Earth. The consequences of these phenomena can be unpredictable, including an increase in the level of ultraviolet radiation, which negatively affects human health, agriculture and ecosystems in general. Therefore, there is an urgent need to develop strategies aimed at reducing the negative impact of space activities.

The main measures to minimize environmental risks are: development of more environmentally friendly rocket engines, in particular based on «green» hydrogen, which does not produce greenhouse gases; reducing the frequency of launches by optimizing launches and commercializing space technologies; implementing strict regulatory standards to limit emissions and monitor their environmental impact; investing in research into methods to restore the ozone layer and combat climate change.

Sustainable development of the space industry is possible only if environmentally friendly approaches are integrated into all aspects of its operation. Implementation of such measures will not only minimize the environmental impact of space launches, but will also help preserve the Earth's ecosystem for future generations.

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