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The Environmental Impact of the Growing Space Industry

On October 4th, 1957, the USSR launched the first satellite, Sputnik, into space marking the beginning of space exploration. Only 12 years later, Neil Armstrong set foot on the moon as the first human on another celestial body. Now, with up-and-coming space companies developing revolutionary technologies, it is obvious that space exploration is a continuously growing industry. As people are awestruck by the seemingly endless possibilities of space exploration, many tend to overlook the potential consequences of the space industry. The most concerning consequence of the space industry is the impact that several launches may have on the environment, both locally and globally. The rapid growth of the space industry has the potential to cause severe environmental harm, potentially leading to both direct and indirect regulations, impacting key stakeholders of the space industry.

The space industry is growing quite quickly, especially with commercial companies starting to take a larger role with federal support and greater incentives. Analyzing a dataset containing all space missions from 1957-2019 gave further insight to the history of space flight and the growth of the space industry (Agirlcoding 2020). Figure 1 displays the number of launches each year separated by federal and commercial companies. From the graph, it's clear that there is a recent increase of

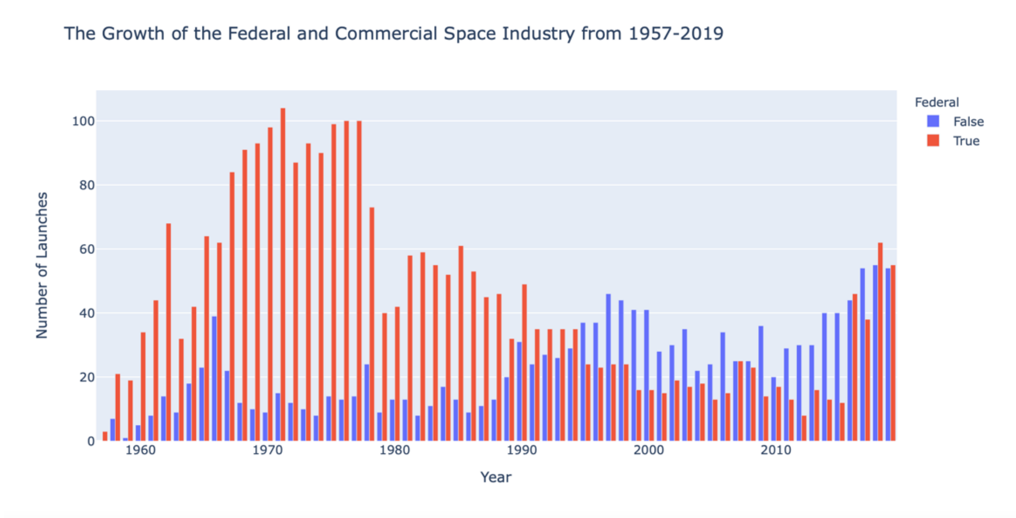

Fig 1: Growth of the Space Industry

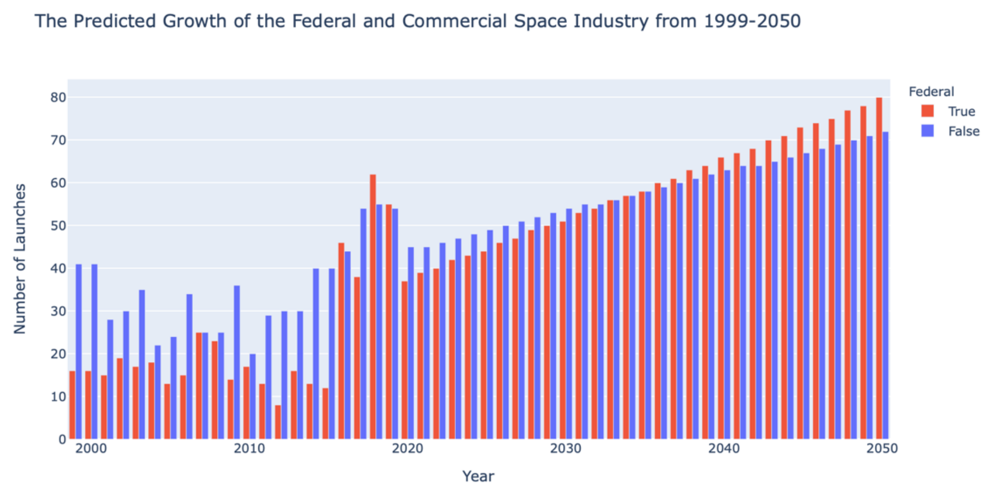

Fig 2: Predicted Growth of the Space Industry

launches, mainly driven by the commercial sector. To further explore the potential growth of the space industry, a linear regression model was created by looking at the past 20 years of space missions, shown by Figure 2[1]. By this model, the growth of the space industry could reach 150+ launches annually by the year 2050, highlighting the rate of growth of space exploration. The growth is assuming a purely linear relationship, which likely will not be the case as many factors will spur an even greater increase in number of launches per year.

One of those factors is the commercial sector that is playing a larger role in the space industry through support from federal entities and more options to finance expensive space missions. Currently, the commercial space industry is investing much more capital than the federal sector. In 2015, $323 billion was spent solely on rocket and space related activities globally. 40% of that spending was generated by commercial space products, 37% came from commercial infrastructure and support industries, while the rest of the 23% was spent by the federal sector (Canis 2016). The commercially dominated spending in the space industry emphasizes the growing number of launches within the commercial sector. Much of this growth can be attributed to the federal government supporting these private companies' ventures of space exploration. The Commercial Space Launch Act caused NASA to sponsor many private companies to develop space technologies by providing capital (Canis 2016). Furthermore, the commercial sector has more opportunities to raise capital through venture capital, investments, and other private financing options (Canis 2016). The combination of the commercial sector's innovation, federal support, and private financing options will spur significant growth within the space industry. Overall, the space industry will continue to grow at a rapid pace, likely led by the

[1] The full code of the exploratory data analysis/linear regression model and more graphs can be accessed through the additional file that was submitted titled "Analysis of Space Missions.html". All code and graphs were created by Daniel Tohti (me).

commercial sector, requiring further consideration of potential environmental consequences caused by an increasing number of launches.

The leading environmental concern of a growing space industry is the ozone depletion that stems primarily from different propellants, which could lead to increased exposure to dangerous UV radiation. There are four main different types of propellant that are currently used: solid propellants, liquid oxygen (LOx)/liquid hydrogen (H2), LOx/hydrocarbons (kerosene), and UDMH/N2H4 (hypergolic) propellants (Dallas, Raval, Gaitan, Saydam, Dempster 2020). The main exhaust products, significant launch vehicles, advantages and disadvantages are displayed in Figure 3, highlighting the large environmental impact of solid propellants along with the

Propellants	Main emission products	Significant launch vehicles and launch systems associated with this propellant	Advantages	Disadvantages
$Al/NH_4ClO_4\pm$ HTPB (solid)	HCl, H_2O, CO_2, NO_x, Al_2O_3, soot	Titan II (0), Titan IIIA/C/D/E (0), Titan IV-B (0), Delta II (0), Space shuttle (0), Ariane 5 ECA/ES (0), Atlas V (0), H-IIA/IIB (0), GSLV (1), PSLV (0, 1, 3)	• Easy to store • High propellant density • Relative design simplicity of engine • High thrust	• Relatively large environmental impact • Low specific impulse relative to LREs • No throttling or shut down
LOx/LH_2	H_2O, H_2, OH, NO_x	Space shuttle (1), Saturn I/V (2), Delta IV (1, 2), TitanIIIE (3), Atlas III/V (2), H-IIA/IIB (1, 2), Ariane 1/2/3/4 (3), Ariane 5 ECA (1, 2), Ariane 5 G+, GS, ES (1), GSLV (3)	• Low environmental impact due to water vapour exhaust • Highest specific impulse	• Requires cryogenic storage due to extremely low boiling point of LH_2 (-252.87 °C) • Low density • Difficult to handle due to temperature requirements and explosion risk
N_2O_4/UDMH ± N_2H_4(hypergolic)	H_2O, N_2, CO_2, NO_x, soot	Delta II (2) Titan II, Titan IIIA/B/C (1, 2, 3), Titan IIID/E (1, 2), Titan IV-A/B (1, 2), Long March 1-4 (1, 2), Proton (1, 2, 3), Ariane 1/2/3/4 (1, 2), Ariane 5 G+, GS, ES (2), GSLV (0, 2), PSLV (2)	• Can be stored for long periods • Relative design simplicity of engine	• High toxicity • Difficult to handle due to safety concerns
LOx/RP-1 (kerosene)	CO_2, H_2O, CO_x, OH, NO_x, soot	Delta II(1), Titan I (1), Atlas III (1), Delta I/II/III (0), Saturn I/V (1) Falcon-9 (1, 2), Atlas V (1), Soyuz (0, 1, 2), Electron (1, 2), Angara (0, 1, 2)	• High propellant density • Relatively easy to handle • More affordable than LH_2	• CO_2 and black soot emissions contribute to climatic warming

Fig 3: Main Propellants and Characteristics

toxicity of hypergolic propellants. Ozone depletion caused by chemical propulsion can be local or global depletion. A study on solid propellants revealed that there was nearly 100% local ozone depletion over an 8km exhaust plume 30-60 minutes after launch (Dallas et. al 2020). After a few days, the ozone layer does approach normal rates, but pockets of depletion remained (Dallas et. al 2020). Global atmospheric models for solid propellants unveiled a 0.25% annual ozone depletion based on 9 launches per year (Dallas et. al 2020). Because the space industry exceed 100 launches a year, close monitoring of solid propellants' impact on ozone depletion is unavoidable. Both liquid and hypergolic propellants aren't as significant in ozone depletion as solid propellants. Based on launching 9 Space Shuttles (LOx/hydrogen fuel) and 6 Titans (hypergolic fuel) annually, the total global contribution to ozone depletion was 0.001% (Bennett, Hinshaw, Barnes 1992). Chemical propulsion is a significant contributor to depletion of the ozone layer that protects life on Earth from harmful UV radiation, which requires regulation of propulsion, especially solid propellants.

Another significant consequence of a rapidly advancing space industry is the impact chemical propulsion has on climate change. Two main exhaust products are the contributors to a greenhouse effect: black carbon, a product of LOx/kerosene fuels, and alumina particles, a product of solid propellants (Dallas et. al 2020). Black carbon, or more commonly known as soot, is an extremely dangerous contributor to global warming because it traps more heat than CO2 and alumina particles (Dallas et. al 2020). The studies that reveal climate change as a potential consequence of the space industry have only come out recently. In fact, in the 1990s, many believed that the impact that chemical propulsion had on global warming was negligible (Bennett et. al 1992). A more recent study showed that having 1000 launches annually would cause the impact of the space industry on climate change would be comparable to the airline industry (Dallas et. al 2020). Outside of the direct impact to climate change of chemical propulsion, the acquisition of hydrogen for LOx/H2 fuels is another concern. Currently, the hydrogen used within the space industry is mostly from gray hydrogen, which is collected through a process called steam-methane reforming. Steam-methane reforming creates hydrogen and CO2 from methane, contributing to global warming through CO2 emissions. Chemical propulsion's direct and indirect effect on global warming is especially dangerous because a warmer stratosphere could accelerate ozone depletion, which is already impacted by the space industry. On top of solid propellants, propellants that use hydrocarbons, or kerosene, should be closely monitored as well to prevent an unchecked distribution of black carbon in the atmosphere.

The last significant consequence of a quickly developing space industry is the concern of ecological toxicity from both solid and liquid propellants and poor planning of stage separations. Ecological toxicity is mostly reflected by the occurrence of acid rain and direct damage to the local environment, through the initial launch or debris from stage separation. Much of the local pollution occurs from the large emission of combustion products from solid propellants during the start of the launch, also known as the ground cloud (Chernov 2021). Figure 4 illustrates the formation of acid rain from the ground cloud as the emissions mix with clouds, resulting in acid rain with a pH as low as 0.5. In 1975, the ground cloud from a Titan III launch mixed with a

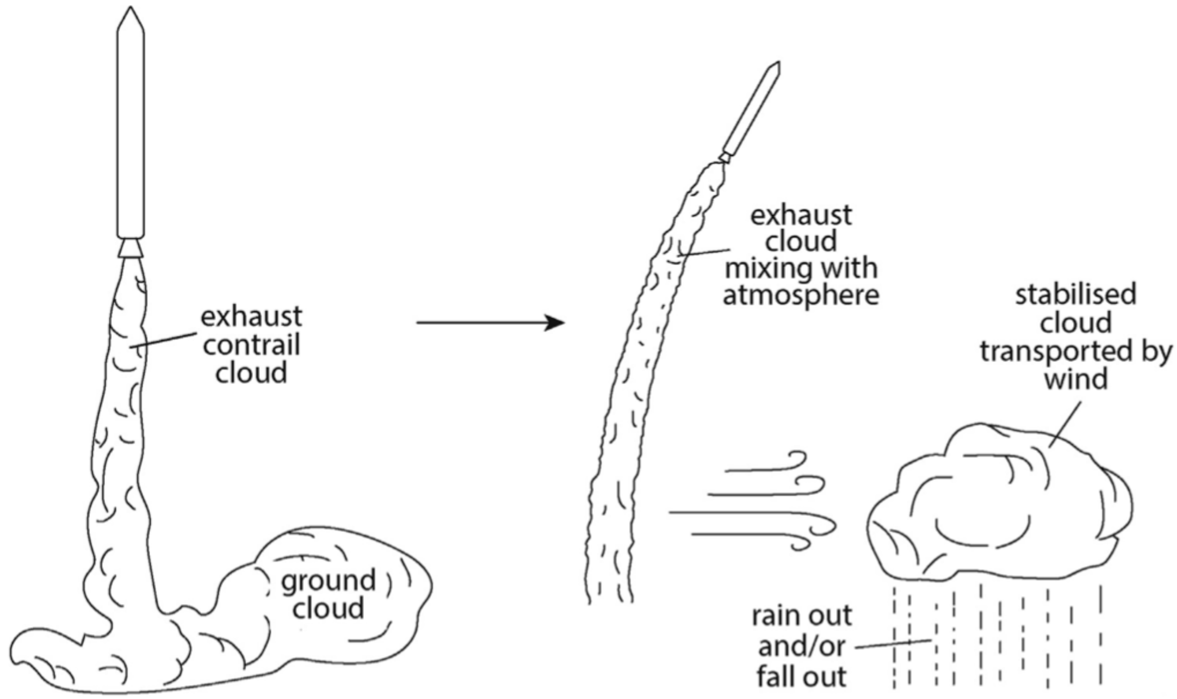

Fig 4: Formation of Acid Rain

nearby rainstorm and caused horrible acid rain to a nearby community (Dallas et. al 2020). The main propellant that contributes to an acidic ground cloud is solid propellants. Solid propellants further damage the nearby soil and bodies of water. The HCl from the exhaust in solid propellants is extremely toxic to the soil around the launch site because it rapidly reduces the pH of the soil and can significantly increase the levels of Al, Cd, Cr, and Mn, which could all lead to poor soil quality (Bennett 1992; Dallas et. al 2020). Furthermore, nearby sources of water are acutely affected by solid propellant exhaust. After a launch, the pH in water can drop from 7 to 1 but can recover back up to normal levels nearly three days after a launch (Dallas et. al 2020). During the recovery time though, marine life can be impacted as the abrupt pH drop can damage fish gills and even kill them (Dallas et. al 2020). The exhaust from solid propellants is a direct contributor to ecological toxicity, further highlighting the need to monitor solid propellants. Liquid propellants, namely hypergolic propellants, contribute significantly to the rise in ecological toxicity. UDMH, a main ingredient for hypergolic propellants, is a highly toxic and corrosive material and was coined the nickname the “Devil’s Venom” (Koroleva, Krechetov, Semenkov, Sharapova, Ledney, Karpachevskiy, Kondratyev 2018; Dallas et. al 2020). This fuel is extremely harmful to the local environment as it can significantly deteriorate local plants and vegetation (Koroleva et. al 2018). Because UDMH is primarily used in the Russian Proton rocket, many of the studies of hypergolic fuels are done in the Russian/Kazakhstan region. Main concerns of UDMH stemmed from poor planning of stage separation. When stage separation occurred on the Proton rocket, there would often be residual UDMH within the fuel tank, and, if the fuel tank didn't explode upon impact, it would lead to destruction of vegetation through both mechanical and chemical disturbances (Koroleva et. al 2018). Figure 5 displays the effect of poor stage separation planning through the obvious vegetation destruction around the impact of the first stage of the Proton rocket. Surprisingly, launches during the winter had less of an ecological impact because the large amounts of snow within the Russian/Kazakhstan region protected the underlying vegetation (Koroleva et. al 2018). Ultimately, ecological toxicity is an important consequence to consider and monitor when observing the increasing rate of growth of the space industry.

Fig 5: Impact of Stage Separation

All the potential consequences above spur the need for both direct and indirect regulation of propellants and launches, which will be met with resistance from key stakeholders in the federal and commercial sector. First, the use of solid propellants and hypergolic propellants should be directly disallowed as they are directly causing severe ozone depletion, contributing to climate change, and creating toxic ecosystems (Novikov, Tatarinov 2019). Furthermore, the use of kerosene propellants should be limited indirectly with a tax on the use of a certain amount of kerosene propellants because of black carbon's contribution to global warming. Lastly, incentives in the form of capital should be provided to those who utilize green hydrogen fuel (hydrogen sourced from electrolysis). Green hydrogen fuel has the least environmental impact, making it a promising choice for future launch vehicles. Regulating these harmful chemical propellants and encouraging the use of sustainable fuels will prevent the growing demand of space exploration from negatively impacting the Earth. Outside of the fuels, the structure of the launch vehicles themselves must meet certain expectations before launching. There must not be any residual fuel in any tank after stage separation, which can be implemented through additional tests (Novikov et. al 2019). Also, the drop zones for stage separations must be concentrated to a tighter area because, currently, there isn't any such restriction (Novikov et. al 2019). Having a concentrated drop zone will prevent widespread ecological toxicity and make clean-up easier. Another consideration for launches is the location of the launch site. Ideally, the launch site should be placed in areas where there are alkaline soils because of the high buffering capacity against sudden drops in pH levels (Dallas et. al 2020). With these restrictions, certain stakeholders are bound to rely on creativity and innovation to work around the regulations. For example, Russia will likely have to create a whole new launch vehicle as their only rockets (Proton and Soyuz) use hypergolic or kerosene fuels (Koroleva et. al 2019). NASA would likely investigate reusing the Space Shuttle's RS-25 engines because RS-25s use hydrogen fuels. In the commercial sector, many private companies will have to explore creative ideas, like SpaceX's reusable booster stage, to ensure sustainability within the space industry supported by the federal government. Although regulations may be restricting, they are necessary to prevent the space industry from becoming a bigger environmental problem in the future, and these restrictions could even spur innovative technologies.

After exploring the evidence of space exploration rapidly growing and the potential consequences of an unchecked industry, implementing the above regulations are extremely important to stay on the path to carbon neutrality. Perhaps even more important than the regulations is the need for further research because there are still many unknowns about space exploration's impact on the environment. The possibilities of this industry is certainly endless as humanity strives to unravel the mysteries of the universe, but as engineers, such as myself, look to the stars, we mustn't forget the only planet that we call home.

References

Agirlcoding. (2020). All Space Missions from 1957 (Version 6) [This DataSet was scraped from https://nextspaceflight.com/launches/past/?page=1 and includes all the space missions since the beginning of Space Race (1957)]. Retrieved from https://www.kaggle.com/agirlcoding/all-space-missions-from-1957

Bennett, R., Hinshaw, J., & Barnes, M. (1992). The effects of chemical propulsion on the environment. *Acta Astronautica*, *26*(7), 531–541. https://doi.org/10.1016/0094-5765(92)90124-2

Canis, B. (2016). Commercial Space Industry Launches a New Phase. *CRS Report*, *1*(1), 1–20. https://sgp.fas.org/crs/space/R44708.pdf

Chernov, I. V. (2021). Scenario Analysis of the Impact of Rocket and Space Activities on the State of the Environment. *IFAC-PapersOnLine*, *54*(13), 145–149. https://doi.org/10.1016/j.ifacol.2021.10.435

Dallas, J. A., Raval, S., Gaitan, J. P. A., Saydam, S., & Dempster, A. G. (2020, January 28). *The environmental impact of emissions from Space Launches: A comprehensive review*. Journal of Cleaner Production. Retrieved October 28, 2021, from https://www.sciencedirect.com/science/article/pii/S0959652620302560

Koroleva, T. V., Krechetov, P. P., Semenkov, I. N., Sharapova, A. V., Lednev, S. A., Karpachevskiy, A. M., Kondratyev, A. D., & Kasimov, N. S. (2018). The environmental impact of space transport. *Transportation Research Part D: Transport and Environment*, *58*, 54–69. https://doi.org/10.1016/j.trd.2017.10.013

Novikov, V. K., Novikov, S. V., & Tatarinov, V. V. (2019). Possible directions for reducing the influence of the rocket and space industry on the environment. *XLIII ACADEMIC SPACE CONFERENCE: Dedicated to the Memory of Academician S.P. Korolev and Other Outstanding Russian Scientists – Pioneers of Space Exploration*. Published. https://doi.org/10.1063/1.5133233