Reusable Rockets and the Environment

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May 8th, 2020

Introduction

Many studies have been conducted on the environmental impact of automotive vehicles, but less research has been done on the effects of orbital launch vehicles. This literature review addresses the question, *what are the environmental effects of reusable rockets?* The environmental effects that are considered include pollution to the atmosphere, soil, and low Earth orbit in the form of space debris. Also, reusable orbital launch vehicles are specifically considered because their reduced costs could increase launch frequency. The impact of rockets in general has been difficult to quantify because rockets are not launched very often, and they mostly operate in space. Research has shown that launch prices are decreasing while their total environmental effects are unknown (Jones, 2018). However, research agrees that space debris is a considerable threat to future space activity that will only get worse, but there is no consensus as to when the problem will be too great (Noble, et al).

Orbital launch vehicles are rockets that can insert payloads with at least 2000 kilograms of mass into low Earth orbit. There are many rockets currently operational with this capability, but only two are reusable: The Falcon 9 and Falcon Heavy. Unlike their conventional counterparts, these rockets do not eject and discard their first stage. Instead, they recover and reuse it. However, conventional and reusable rockets are similar because they discard their second stage after their payloads have been deployed.

The research conducted in this literature review was taken from databases accessed through the UC Merced library website. Due to the limited research on the environmental effects of rockets with respect to the ocean, it was not mentioned. There was however, substantial research on the effects to soil, the atmosphere, and low Earth orbit. It is difficult to quantify why there is so little research done on the environmental effects of rockets and the ocean but it could be for several reasons. First, maybe there has been research done, but it is not accessible through the available databases. Second, being down range is a very dangerous, dynamic environment making it very difficult to study, especially out at sea. Third, launches are so infrequent, their overall effects might be negligible compared to other forms of oceanic pollutants.

Pollution

Reusable rockets are superior to conventional, single-use rockets because they are cheaper to launch. This might be a direct result of their reusability, or it might be because of the inherent advantages these new commercial space launch companies hold over their antiquated competitors. If cars and planes only had single-use capabilities, then using them would be extremely expensive. Also, pollution would be considerably less because their cost would limit their overall use. Whether reusability will increase the frequency of launches, and in turn, increase their environmental impact has yet to be determined.

To better understand the possible environmental effects that reusable rockets may have, it is important to consider the impact conventional rockets have. They can be compared to each other because they operate the same, except reusable rockets obviously launch multiple times. Rockets pollute, but their total impact is not fully quantified. Rockets produce noise, visual and thermal radiation, chemical emission, and debris pollution (4). There have not been enough studies on the impact of rockets even though they are extremely wasteful. (4; Zhubatov et al., 2019). It is true that the reusable rockets of today do not discard their first stage, which would decrease their terrestrial impact. They do, however, discard their second stage which could affect the environment as well.

Like previously mentioned, rockets also pollute through their chemical emissions, mainly in the forms of exhaust byproducts and fuel spills. Rockets are solid or liquid fueled, or both. For example, the non-reusable Russian Proton rocket used unsymmetrical-dimethylhydrazine (UDMH) and nitrogen tetroxide, while the American Space

Shuttle used a combination of a different liquid propellant with two strap-on, solid fueled boosters. Because their fuels differed, their pollutants also differed.

Despite the fact that it is known what types of combustion byproducts rockets produce, their effect on the atmosphere is not well quantified. Rocket plumes, which are the large columns of smoke produced by the rockets, were shown to travel thousands of kilometers. This gives them unique properties compared to other forms of atmospheric pollution (Gorkavyi, 2020). Specifically, exhaust byproducts of the Space Shuttle mission STS-118 were detected and identified as containing ionized iron and ionized water vapor near the pole (1). The exhaust plume produced unusually thick mesospheric clouds and water vapor which traveled unusually quickly (1). The observations suggest wind velocities greater than 100 meters per second, which is about one third the speed of sound (1). The plumes are said to have ballistic trajectory, which means that they are able to travel farther and faster than other forms of pollution (1). The effect of this phenomena is unknown, but it might be significant if launches increase. As of now, there is little research quantifying the overall effects of greenhouse gases produced by rockets, probably due to the fact that they are infrequent. For example, there were only twenty-three launches from the United States in the year 2017 (Weinzierl, 2018)

Another way that rockets pollute, which usually goes unnoticed except in the immediate vicinity of a launch, is the acoustic pollution (Koroleva et al., 2018; Lin et al., 2017). Rockets are extremely loud because their propellants are combusted then accelerated to many times the speed of sound, which creates acoustic shock waves. Research showed that concentric traveling ionospheric disturbances were triggered by acoustic shock waves produced by the reusable Falcon 9 rocket (5). This phenomenon can alter the upper atmospheric winds because they are linked to the ionosphere (5). These disturbances were shown to travel extremely fast and extremely far, up to a thousand kilometers (5). The full impact of these ionospheric disturbances is still unclear since they were only recently discovered.

Despite not knowing the complete atmospheric effects of rocket pollution, research quantifies the terrestrial impact. Various measures of the environmental effects were detailed when observing crash sites (4; 10). In the case of the Baikonur Cosmodrome in central Kazakhstan, rocket stages are discarded over land because of the launch pads' locations (4; 10). This presents many environmental issues because launch vehicles like the Proton and Soyuz rockets use toxic chemical propellants like UDMH and kerosene, respectively.

UDMH is a carcinogen and mutagen categorized in the first danger class of chemicals (4; 10). The effects of UDMH on the soil fauna showed that doses greater than 200 milligrams of UDMH per kilogram of soil killed all microbial life. Interestingly though, it was shown that at low doses, growth, development, and productivity increased (4). This was in agreement with other research even though the doses by which stimulated growth was claimed are different. In one study, doses up to one gram of UDMH per kilogram of soil stimulated growth, while another study suggested that doses less than a tenth of a gram of UDMH per kilogram of soil stimulated growth (4; 10). There is general agreement, but slightly different values.

There is also slight disagreement about how long UDMH can continue to contaminate. One study found that UDMH was rarely found in significant concentrations just after a year (4). Another study showed that UDMH contaminates for a longer period of time by measuring trace amounts four years later (10). As of now, current reusable rockets do not use UDMH, but future designs might because it is a reliable and popular propellant.

Other research revealed the environmental impact of the Soyuz rocket, which is interesting because it shares the same propellant as today's reusable rockets (Harris & Landis, Mar 2019; 10). Research suggested that the biggest hazard came from rocket fueled fires (10). Similar to UDMH, a toxic amount of fifty to 500 grams of kerosene per kilogram of soil severely depletes microbial life (4). It was also demonstrated that kerosene did not seem to continue to contaminate over time to the same level as UDMH (4).

However, the impact of kerosene fueled reusable rockets will continue to be undetermined until an increase in launches is realized. Because they recover the first stage, they will not contaminate the surrounding area in the same way as the Soyuz, even if the number of launches increases.

Since the Soyuz and current reusable rockets use the same propellants and discard their second stages, their pollutants can be assumed to be similar. With respect to the Soyuz, the second stage causes less environmental impact (4). Sixteen different second stage crash sites of the Soyuz rocket were observed and an insignificant amount of kerosene was detected (4). Also, distribution of rocket debris was greater than the first stage crash sites because the second stage descends from much higher altitudes and is likely to break up and spread out (4).

Rockets pollute, but a sustainable approach may or may not cause less pollution. Sustainability means reusability, but reusability in the long term is expected to reduce prices more, which is expected to increase the number of launches (3). A case study was conducted in which a non-reusable Falcon 9 and a reusable Falcon Heavy were compared (2). The two rockets were analyzed using a sustainability assessment which evaluated the environmental, economic, and societal impact of the two rockets. The environmental portion of the study was conducted on a per unit mass basis where the non-reusable Falcon 9 was the baseline.

The study demonstrated that the reusable Falcon Heavy reduced costs by 65% and global warming potential by 64% (2). Global warming potential is an important metric by which different pollution emitters are standardized and used to be compared to one another. Showing the advantages of a reusable rocket, the large reduction in global warming potential came from the production of the vehicle and not the actual launch (2). This reduction in global warming potential is significant and would only be offset by an increase in launches. It could be expected that reduced costs will increase launches, but it is still unclear whether reusable rockets are the direct cause.

Rockets also pollute the region known as low Earth orbit in the form of defunct satellites and debris of different sizes. Once space debris makes impact on other objects in space, more debris is created. Even small, undetectable pieces can create more. This phenomena can lead to a runaway cascading effect known as Kessler Syndrome, where space debris is continuously generated. The total amount of dangerous space debris is unknown because NASA's Space Surveillance Network can only effectively track objects of at least ten centimeters in size (Slíz-Balogh et al., 2020). This means that the number of objects in space less than ten centimeters in size is an estimate. Because of this, the time period when the onset of Kessler Syndrome might occur is also an estimate (7; 8).

A solution to space debris that is often considered is the deorbit of old satellites (7; 8). This keeps the overall population of satellites at a minimum to reduce the risk of debris generation. If the risk becomes too great and old satellites are deorbited, they will burn up and crash, polluting the atmosphere, ocean, or land. Research showed an estimated ten to forty percent of larger objects may survive reentering, impacting the ground (8). This is currently the only way to clear up and manage space debris because no other practical alternative exists.

Most satellites and space debris are concentrated in the low Earth orbit region, which makes it a hazardous environment as it becomes more crowded (7). Over the last ten years, revenues increased 92% while the amount of space debris ranging from one kilogram to 8300 kilograms has grown 124% from 2006 to 2010 (7). A technology that could prove essential in managing space debris would be an active debris removal (ADR) system (7). The Inter-Agency Space Debris Coordination Committee is an organization of scientists from around the world that is helping to solve the problem of space debris using active debris removal techniques (7). Developing this technology would protect the $300 billion in revenue from potential danger due to space debris (9).

Research shows that the number of satellites has grown considerably in recent years, totaling over 14,000 in low Earth orbit (McDowell, 2020). This does not include the amount of space debris in the same region, which is approximately 34,000 objects larger than ten centimeters, 900,000 objects between one and ten centimeters, and 128 million objects from one millimeter to one centimeter in size (8). It is projected that as the growing number of satellites increases, the number of collisions will also increase, potentially accelerating the onset of Kessler Syndrome (6; 8).

Despite this, the time frame under which this will become an overwhelming danger is unknown because of the uncertainty in the amount of small debris and because the satellite population is increasing in low Earth orbit (8). New mega constellations like SpaceX's *Starlink* are in their early stages of development, but final versions are going to further populate low Earth orbit. These constellations are estimated to contain 12,000 to 30,000 individual satellites in order to increase internet coverage (6). Most research suggests that the onset of Kessler Syndrome would most likely occur over long periods of time, but it is noted that certain events could accelerate it (6; 7). Some recommend that discarding old satellites within twenty-five years of their operational life would be a sufficient solution, at the same time it is estimated that the risk of collisions increased seven-fold over the past ten years (6; 7).

It is still unclear what environmental impact demand for these new satellite constellations will have because it is too early to tell. As of now, 299 *Starlink* satellites have been deployed, all of which were launched on the reusable Falcon 9 (6). As of now, not enough time has passed to allow for the amount of research required to determine the total environmental impact of a crowded low Earth orbit. It was noted, however, that at a minimum, *Starlink* satellites will reflect sunlight, affecting twilight and long-exposure cosmological observations (6).

Cheaper Launches

Sustainability and overall competitiveness of the space industry is what has been shown to be one of the major driving factors that is decreasing the price of launches (2; 3; 9). Sustainability is the balancing of the environmental, economic, and societal factors involved in production. Usually, improving a product to make it more sustainable also improves cost and overall performance (2). In the case of NASA's Space Shuttle, the fact that it was reusable did not necessarily make it cheaper to use. The Shuttle cost about one and a half billion dollars to launch 27,500 kilograms to low Earth orbit, but SpaceX, a privately-owned launch company, advertises a cost of sixty-two million dollars to launch 22,800 kilograms to the same low Earth orbit using their reusable Falcon 9 rocket (3). That is a cost to mass launch ratio of $54,000 per kilogram and $2,720 per kilogram respectively (3). Since both spacecraft are reusable, other factors are affecting their comparative costs.

The commercial sector has caused disruption in the space industry because it used to be dominated by centralized control (3; 9). The primary entity buying space launches was the United States government, which resulted in a sort of monopoly (3). The decrease in launch cost can also be attributed to the commercial space industry becoming more competitive. Commercial production methods include simplified vehicles, increased production and launch rates, industrial design and production, optimized minimum cost, reduced parts, increased design margins, reduced instrumentation, and design for production and operation (3). It was shown that for the reusable Falcon Heavy, the price for launch per unit mass was further reduced by over $6,000 per kilogram to the higher, more costly geostationary orbit (2).

The general structure of commercial companies as compared to government agencies also lead to reduced costs (9). The literature revealed that smaller workforces, in-house development, less management layers, less infrastructure, and commercial culture are what decreased costs (3). The leader of the United States commercial space industry, SpaceX, is a prime example of these practices (3). For example, they employ the core principle which states that simplicity enables both reliability and low cost (3). In NASA's case, the Shuttle was developed and operated in the exact opposite manner, with many complications including 10,000 contractors just to operate the spacecraft (3).

There is, however, some ambiguity in research regarding decreased launch prices. Some research showed through life-cycle assessment, the reusability of the Falcon Heavy rocket drastically reduced prices and other impacts, compared to a non-reusable Falcon 9 rocket (2). On the other hand, general market competitiveness might be more strongly attributed to the decrease in launch price, especially when comparing the Space Shuttle and a reusable Falcon 9 rocket (3; 9). Both are reusable, but the Shuttle was designed and operated in an inefficient manner. The reusable Falcon 9 and Falcon Heavy are cheaper to launch and have been reused, but not yet enough times to offset the higher developmental costs associated with reusability (3).

Conclusion

Not enough research has been done to fully quantify the environmental effects of reusable rockets. The effects of conventional rockets on the environment are not yet completely understood, and the effects added by reusable rockets are also unknown. More research has to be done to examine the atmospheric and terrestrial effects since not enough data has been collected on these issues. Since reusable rockets provide a large reduction in global warming potential, only a large increase in launches would offset their initial sustainability. Reusable rockets are still new, and their reduction of launch cost has not yet proven to mean a significant increase in launches. It is only an assumption that the decrease in cost will continue to increase the launch frequency.

Space debris is a byproduct of these space activities, and its potential danger is mostly agreed upon. However, the proposed solutions to combat this problem have different levels of urgency. It is projected that launches will increase, which will create more space debris. The hazards associated with space debris will force the removal of old satellites, which currently requires deorbiting them. This will increase the environmental effects on the planet because they will be discarded over the ocean after burning up in the atmosphere. Although this is not a direct consequence of reusable rockets, it is a function of satellite population, which could increase due to the fact that launches are becoming cheaper. Still, not enough time has passed to accurately determine whether reusable rockets will directly cause these things to happen.

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