THE ENVIRONMENTAL EFFECTS CAUSED BY CONTINUED SPACE EXPLORATION

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By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Space exploration has been an expanding field of technology around the world since the 1950s. Starting with the space race to send a human beyond our atmosphere, followed by the landing on the moon, it can be seen that there is a rapid desire to learn more about what is beyond our Earth. This desire has resulted in an increase in space missions. Over the past year, there has been an increase in rocket launches from 135 successful launches in 2021 to 180 successful launches in 2022 (Snow, 2023, p.2). This trend is not expected to slow down either. For example, as of March 18, 2023, SpaceX has had 19 successful launches in 2023 (Kurkowski, 2023). However, this increase in space exploration missions comes with harmful environmental consequences. These rocket launches release harmful emissions that can lead to ozone depletion in the atmosphere which is a major factor in global warming.

Even though the success rate for missions is high, various space missions can and have failed resulting in the explosion or destruction of the spacecraft. Whether “a rocket self-destructs because it thinks it is going too fast” or the trajectory is off by just a little causing it to disintegrate in Mars orbit, space debris can form (Mehta, 2021).The space debris resulting from failed rocket launches can last up to ten years which leaves room for a substantial amount of collisions (Chen, 2011, p. 545). The space debris from a failed launch, along with the emission created to launch these missions, can outweigh the pros that come along with space exploration.

The STS research analyzes the specific effects that space exploration has on harming the environment as well as how companies can work to mitigate the space debris and pollution risks. This analysis will include an ideal strategy to implement environmental regulations in the design process presented by a Social Construction of Technology (SCOT) (Pinch & Bijker, 1987) framework. The STS research aims to propose that although we can gain helpful insight through space exploration as well as experience something that was once thought of as a dream, i.e. space tourism, that companies should not hastily advance in missions without thinking about the environmental risks. This is tightly coupled with the technical research project which is developing a communications system for a spacecraft that will experience hypersonic flight. The communications system must be able to transmit pressure and temperature data during re-entry of the hypersonic vehicle.

HARMFUL EFFECTS DUE TO SPACE MISSIONS AND WAYS TO REDUCE THEM

THE SPACE DEBRIS ISSUE

According to NASA (2021), there are approximately 23,000 pieces of debris the size of a softball or larger orbiting Earth at up to 17,500 mph. There are then about 500 thousand pieces around the size of a marble followed by approximately 100 million pieces of debris that are only .04 inches. (NASA, 2021). Although the softball sized debris can do considerable damage to spacecraft and satellites, the smaller debris can also cause issues as “even tiny paint flecks can damage a spacecraft when traveling at these velocities” (NASA, 2021, p.2). Figure 1 below provides a visual representation of the space debris orbiting the Earth as tracked by NASA. Each dot represents space debris that is the size of a softball orbiting the Earth.

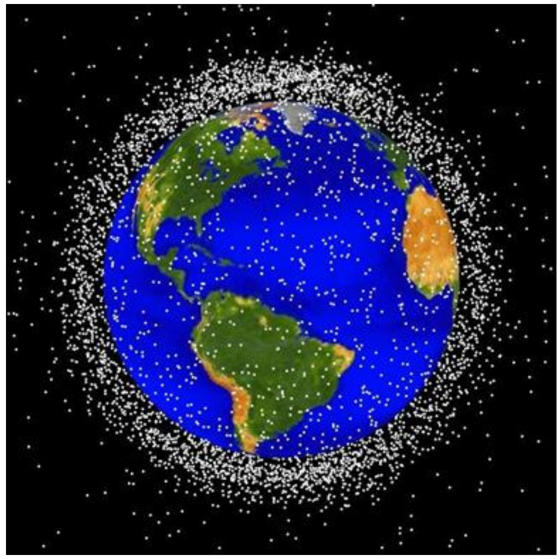

Figure 1: Space debris in orbit about Earth. This figure is a computer-generated image based on NASA's tracking of large space debris (NASA, 2021).

These millions of pieces of space debris orbiting the Earth, as shown above in Figure 1, will only cause more debris to build up. In a report, Shenyan Chen (2011) explains the long-term effects of the space debris problem. Since orbital debris can last up to ten years, there is room for a substantial amount of collisions which can eventually lead to what Chen thinks as one of the most important issues (p.545). That is where collisions between objects are so frequent that they produce additional debris faster than atmospheric drag removes it (Chen, 2011, p. 550). This means that there will only be more space debris added than removed resulting in a forever increasing amount of debris.

Additionally, there exists space debris that leaves space, and re-enters into the atmosphere. There is no immediate danger as the space debris will burn up due to the immense heat upon re-entry. However gasses are released during this process, primarily including nitrogen oxide which leads to ozone depletion (Ryan, Marais, Balhatchet & Eastham, 2022, p. 1).

EMITTED POLLUTANTS FROM ROCKET LAUNCHES AND SPACE TOURISM

It has been emphasized in Ryan, Marais, Balhatchet and Eastham's (2022) article how the atmospheric effects due to the space industry is not something to ignore as this industry is one of the world's fastest growing (p. 1). Additionally, Snow (2023) noted that compared to aviation, which produces about 2.5% of the world's carbon-dioxide emissions, and other industries, aerospace activities produce a relatively low amount of emissions. However these pollutants that are released can do just as much damage to the ozone layer and contribute to global warming (p. 2).

As mentioned above, nitrogen oxide is one of the gasses emitted during the re-entry heating of space debris. Nitrogen oxide (N2O) has been the largest ozone-destroying gas emitted resulting from human activities (Portman, Daniel, & Ravishankara, 2012). Additionally to the N2O produced from space debris, the re-entry process of reusable components, such as SpaceX's reusable rockets, also produce N2O. These reusable rockets also produce chlorine from the solid fuels used, which is another contributor to ozone depletion (Ryan, Marais, Balhatchet & Eastham, 2022, p. 1). Ozone depletion increases the ultraviolet radiation that reaches the earth which poses various health risks such as skin cancer and genetic and immune system damage (Wuebbles, 2022).

Both the aviation industry and the aerospace industry produce emissions that can cause ozone depletion, however they produce them in different levels of the atmosphere. Airline flights are in the troposphere which is the lowest layer of the atmosphere whereas rockets burn fuel in the higher-level mesosphere and stratosphere. In the higher layers of the atmosphere, the only human source of direct emissions in those layers come from the burning of rocket fuel (Snow, 2023, p.3). To make a comparison between black carbon released by different vehicles in different atmosphere levels, Snow presents that black carbon particles from diesel trucks or a commercial flight, which are in the troposphere, dissipate after a few days. On the other hand, black carbon particles from rockets in the stratosphere can last up to 4 to 5 years (Snow, 2023, p. 3). According to the U.S. Environmental Protection Agency (EPA) (2011), "inhalation of black carbon is associated with health problems including respiratory and cardiovascular disease, cancer, and even birth defects." (p.1). Additionally, since black carbon can absorb light as heat, it also contributes to climate change by warming the air, and causing rapid changes in rain patterns. As an emphasis on the harmful effects of black carbon, according to Ryan, Marais, Balhatchet and Eastham (2022), black carbon soot is "almost five hundred times more efficient at warming the atmosphere than all other sources of soot combined" (p. 1).

The increased popularity of space tourism also poses a great concern as it will increase the amount of black carbon produced. Currently, space tourism "emits 50 to 100 times as much emissions per passenger as a long-haul commercial aviation flight" (Snow 2023). This statement supports the claim that the climate effects due to rocket launches can double if space tourism keeps going down its same path and becomes a daily mission after three years. The graph shown below in Figure 2 is a representation of the posing dangers of space tourism. Radiative forcing is the change in energy flux within the atmosphere and is a main factor for climate change (Chandler, 2010).

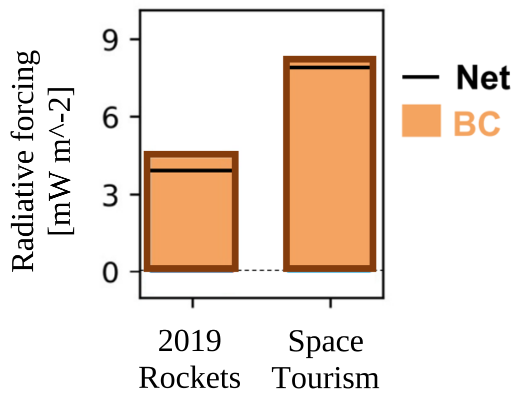

Figure 4: Comparing radiative forcing from rockets and space tourism. Compares the amount of radiative forcing is caused by black carbon (BC), ozone and methane ($O_3$and CH_4), and polar stratospheric clouds (PSCs) between a decade of rockets and 3 years of space tourism (Ryan, Marais, Balhatchet & Eastham, 2022).

In the graph, the right column representing space tourism is only based on 3 years of space tourism activity compared to a decade of emission effects of regular rockets ending in 2019. Within only 3 years of space tourism activity, there is almost double the amount black carbon emissions (shown in orange) which emphasizes how urgent it is to figure out regulations for these new space exploration technologies.

PRODUCTION AND USAGE OF CLEANER FUELS

Clean fuels are typically thought of as those that produce minimal amounts of carbon dioxide or other harmful emissions, thus being ‘clean’ for the environment. However, reasoned by Snow (2023), rocket launch fuels are not renewable and emission concerns come from not only the usage of them, but the production (p. 5). For example liquid hydrogen is thought to be a clean fuel because when it burns it produces water vapor instead of soot. However, adding water to the upper atmosphere, which is typically drier, can have a climate impact and the production of liquid hydrogen is a very carbon-intensive process (Snow, 2023, p. 5). Therefore liquid hydrogen still is not the best solution.

In recent years, various companies around the world have been researching alternative fuels. A space company in Scotland named Skyrora is currently developing a fuel that could be a replacement if made through a process called pyrolysis. Pyrolysis is turning polypropylene, polyester, polystyrene and other plastic waste mixtures into synthetic kerosene. Additionally, Skyrora can use plastics that are metallized and not typically accepted for recycling and plastics that have been UV ray or salt water damaged. Pyrolysis cuts down approximately 70% of the carbon footprint that is generally associated with the production of kerosene (Skyrora Limited, 2023). Another research project is looked at using bacteria. Researchers at Lawrence Berkeley National Laboratory have been looking at "Streptomyces bacteria that would be 40%-50% more energy dense by volume than kerosene" (Snow, 2023, p.6). By using a less dense, bacteria based fuel, rockets can use more fuel by volume that is even more energy efficient, therefore there can be more payload on the rocket, thus ultimately resulting in less overall rocket launched since more payload is going on each trip. A different research group at the University of California, Riverside is looking at ammonia borane, which is a chemical currently used to store hydrogen in fuel cells in electric vehicles (Snow, 2023, p.6). Similar to liquid hydrogen, ammonia borane releases water when it is burned which is a carbon-free alternative. However, as mentioned before, adding water to the upper atmosphere is not always the best solution.

CURRENT REGULATIONS TO MITIGATE RISKS

Currently, there are treaties and regulations in place to combat space debris and the deteriorating ozone layer. First there is the Inter-Agency Space Debris Coordination Committee

(IADC) and their space debris mitigation guidelines. The IADC is an international governmental forum for the worldwide coordination of activities related to man-made and natural debris in space. Agencies involved include ASI (Agenzia Spaziale Italiana), CNES (Centre National d'Etudes Spatiales), CNSA (China National Space Administration), CSA (Canadian Space Agency), DLR (German Aerospace Center), ESA (European Space Agency), ISRO (Indian Space Research Organization), JAXA (Japan Aerospace Exploration Agency), KARI (Korea Aerospace Research Institute), NASA (National Aeronautics and Space Administration), ROSCOSMOS (State Space Corporation), SSAU (State Space Agency of Ukraine), and the UK Space Agency (Inter-Agency Space Debris Coordination Committee, 2019). This handbook created by the Inter-Agency Space Debris Coordination Committee (2020) states that a feasible Space Debris Mitigation Plan be established and documented for each program and project which must include the following:

1. A management plan addressing space debris mitigation activities
2. A plan for the assessment and mitigation of risks related to space debris, including applicable standards
3. The measures minimizing the hazard related to malfunctions that have a potential for generating space debris
4. A plan for disposal of the spacecraft and/or orbital stages at end of mission
5. Justification of choice and selection when several possibilities exist
6. Compliance matrix addressing the recommendations of these Guidelines. (p. 9)

These set of general guidelines will help minimize the amount of space debris that result from space exploration missions. The IDAC handbook adds mitigation measures to minimize break-up of the spacecraft starting from launch, through the operation phase, and ending with the postmission phase to further ensure that as little space debris is produced as possible (Inter-Agency Space Debris Coordination Committee, 2020). In Ryan, Marais, Balhatchet and Eastham's (2022) research article, they mention the Montreal Protocol (p. 1). The Montreal Protocol is an agreement that regulates the production and consumption of ozone depleting substances (ODS). This protocol was adopted in 1987 and is the only UN treaty ever that has been ratified by all 198 UN member states (United Nations Environment Programme, 2022).

Although there are these regulations in place, space debris is still a large problem that may only get worse with an increased space exploration. There is also no doubt that global warming is an issue that is not going away, and the emissions from these space missions are not aiding in solving that issue.

POTENTIAL DESIGN PROCESS FORMAT

With the research and development of alternative fuel sources, there then needs to be an urgency to implement them in major companies. In the aviation industry, researchers investigated 20 leading operators in aviation and analyzed their knowledge and acceptance of climate change mitigation strategies. Out of the 20, more than half recognized the target of achieving a reduction in net aviation carbon dioxide emissions by 50% by 2050 and Sustainable Aviation Fuel (SAF) is widely adopted among the airlines (Leal Filho, Ng, & Sharifi, 2022, p.8). Since the aviation industry is adapting to reducing harmful emissions, the space industry should be next.

In order to attempt to reduce the harmful effects of space exploration on the environment, companies could follow the Social Construction of Technology (SCOT) (Pinch and Bijker, 1987) model shown below in Figure 3.

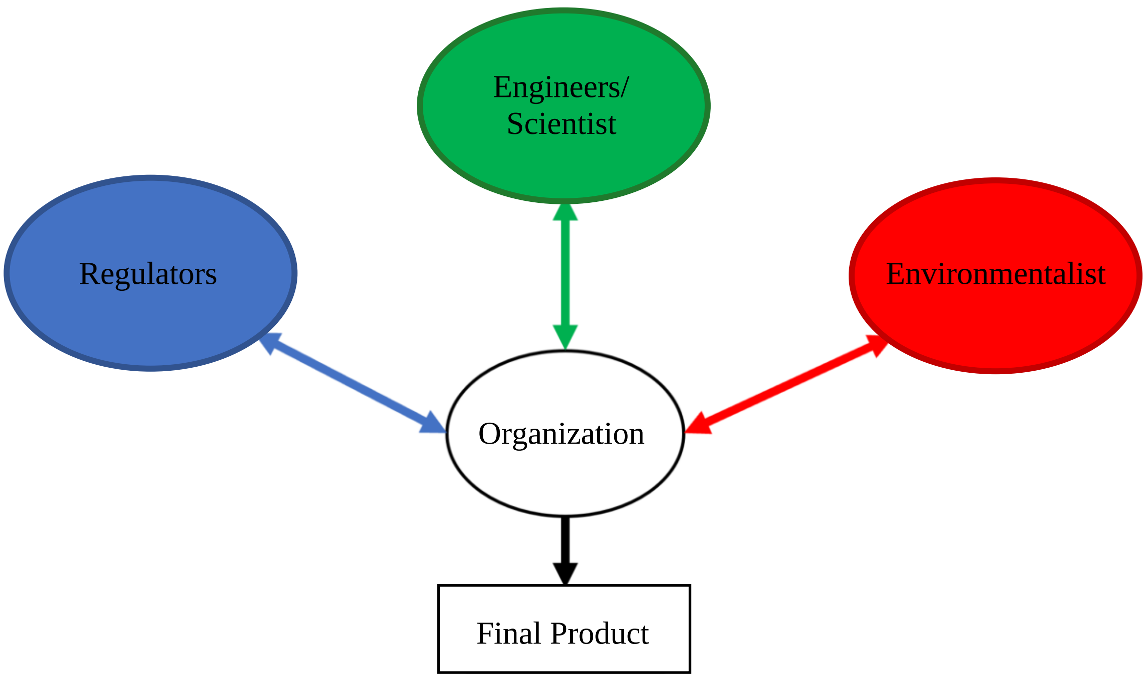

Figure 3: SCOT model for integrating a space exploration product. Three groups, regulators, engineers/scientists, and environmentalists share ideas back and forth with an organization to implement correct guidelines for space exploration technology (adapted by Kaiya Saunders from Pinch & Bijker, 1987).

For this model, an organization, for example SpaceX, would voice their ideas for a product to the other groups. The regulators would then provide them with the guidelines they need to follow in order to minimize the amount of space debris formed. The engineers/scientist will be responsible for designing the spacecraft with the right materials and making sure to test the product sufficiently so there are no accidents in space that can lead to an increased amount of space debris. Then environmentalists can add their input as to what fuel type would be most beneficial to the atmosphere. Throughout the whole design process there will be a back and forth between these three groups and the organization until a final product is produced that meets all the requirements necessary to minimize the environmental harm the space mission will cause.

The desire to learn about the unknown has been common in the development of the world. A majority of the inventions that have arisen have been due to scientists and engineers wondering ‘What if?’ This desire has not diminished as technology has been improving rapidly. However, those who are hasty with wanting to explore need to think about the risks these advancements in technology can have on the environment. With space exploration missions becoming more frequent every year, the harm caused by them has become more notable. The failure of missions have led to increasing amounts of space debris which can then collide with subsequent missions leading to a never-ending cycle of the production of space debris. Additionally these chunks of space debris can release harmful gasses that lead to the depletion of the ozone layer. The emissions released by current fuels also produce black carbon and other harmful oxides that will deplete the ozone layer which can lead to health risks.

There are mitigation efforts being put forth such as the development of cleaner fuels, development and acceptance of guidelines to prevent space debris, and protocols to reduce harmful emissions from rocket launches. However, having companies simply acknowledge the need to implement these strategies does not mean that they will change the way they operate. Future work for the STS research may included performing a similar study as Leal Filho, Ng, and Sharifi by seeing how many leading aerospace companies have acknowledged and began implementing such mitigation measures and comparing their design process to the Social Construction of Technology (Pinch and Bijker, 1987) shown above in Figure 3.

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