Literature review of the environmental impact on the atmosphere of rocket engine emissions during launch, flight and re-entry

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Programa de Ingeniería Aeronáutica

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Literature review of the environmental impact on the atmosphere of rocket engine emissions during launch, flight and re-entry

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in partial fulfillment of the requirements to qualify for the degree

of

Aeronautical Engineer

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This work is dedicated to my parents who have made an effort to support me in each of my stages, difficult moments, happy moments and who support me in my goals to accomplish.

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Contents

List of Figures

List of Tables

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Abbreviations

Al_2O_3 Aluminium oxide or Alumina

BC Black Carbon

CH_4 Methane

Cl Chlorine

Cl_2 Diatomic chlorine

CO Carbon monoxide

CO_2 Carbon dioxide

H Hydrogen

H_2O Water vapor

HCl Hydrogen chloride

HTPB hydroxyl-terminated polybutadiene

LEO Low Earth Orbit

LH_2 Liquid Hydrogen

LO_x Liquid Oxygen

LW Long-wave

l/y Launch per year

N_2 Dinitrogen

N_2O Nitrous oxide

N_2O_4 Nitrogen tetroxide

NO_x Nitrogen Oxides

O Oxygen

OH Hydroxide

RF Radiative Forcing

SW Short-wave

SMF Submicron Mass Fraction

SRM Solid Rocket Motors

UDMH Unsymmetrical dimethylhydrazine

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Abstract

Abstract: The space technology sector is growing rapidly. This leads to an increase in the number of launches to different orbits with positive repercussions. This, however, raises concerns about the impact on the atmosphere. The pollutant emissions from rocket engines depend on the type of propellant used for launch, but regardless, the products that dominate the emissions are CO_2, H_2O, black carbon (BC), and alumina. The footprint of these emissions can be measured as radiative forcing or ozone loss. In this work, emissions from liquid, solid, and hybrid propellants are estimated for three different scenarios, projecting them to 5 and 10 years respectively. According to the results, BC and CO_2 emissions dominate, however, with a much smaller impact than other industries. Without underestimating these emissions, measures must be taken to regulate this industry in a way that allows its growth and, in turn, cares for the environment.

Keywords Atmosphere. Emissions. Environment, Launch. Radiative-forcing. Rocket. Space.

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Chapter 1

Introduction

65 years ago, in 1957, the Soviet Union opened the Space Age with the launch of the first artificial satellite "Sputnik" aboard the R-7 rocket vehicle. Since then, the space industry has achieved great importance for mankind in the social, commercial and military fields. The advances that space technologies have enabled range from telecommunications, positioning services, medicine, to agricultural applications.
The introduction of modern innovative technologies, new investment philosophies, and competitive politic-economic trends around the world has led to the growth of the space industry, the transition from a space era dominated by public or governmental entities to the emergence of private companies that playing an increasingly significant role in Space activities has allowed a positive impact on the space economy. In this way, private companies have invested in novel ways of using space by proposing alternatives such as space tourism, space mining, and space marketing, among others. Moreover, Figure 1.1, shows how the number of countries with a satellite in orbit has increased over the years, and likewise the number of countries having launched a rocket successfully.

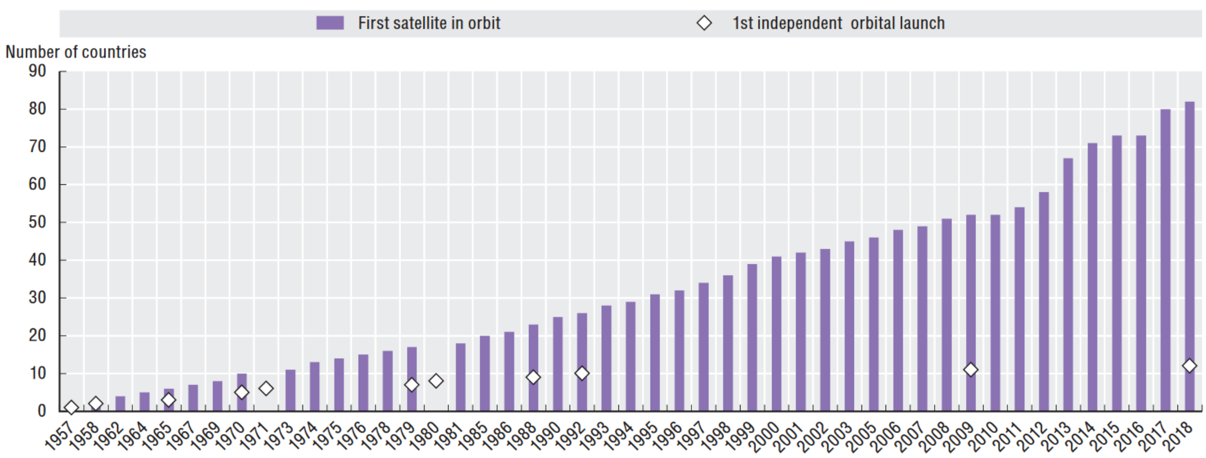

Figure 1.1: Number of countries with satellite and a rocket launch. [39]

Figure 1.2 also allows us to describe the growth of the space industry by looking at the number of objects launched into space including satellites, probes, landers, crewed spacecraft, and space station flight elements launched into Earth orbit or beyond [61].

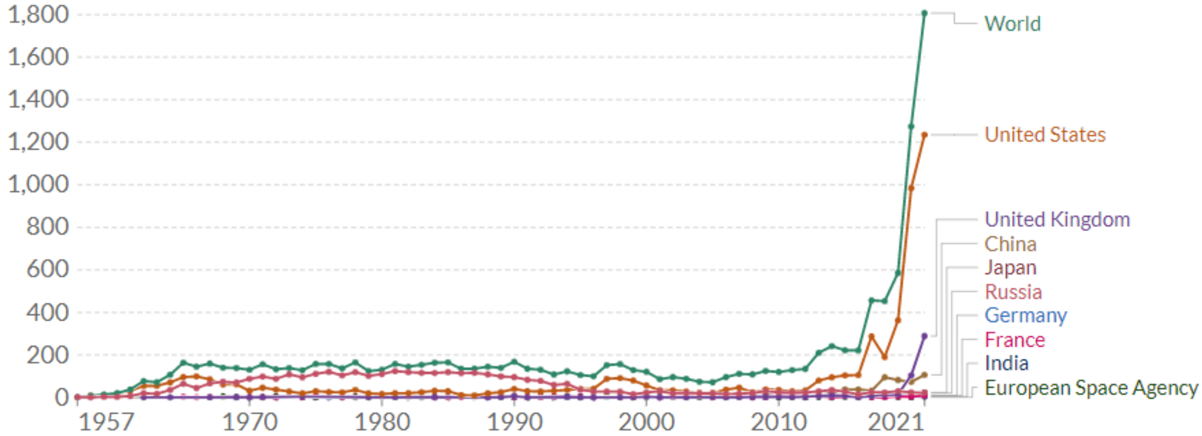

Figure 1.2: Annual number of objects launched into space. [61]

As shown in Figure 1.2, there has been an exponential increase approximately since 2015, one reason for which this can be explained is the reduction in the cost of launch to space by cost per kg to Low Earth Orbit (LEO), as can be seen in the Figure 1.3, which in current dollars plotted various launch systems costs against the first system launch date. The figure shows two notable drops, which was from the Vanguard to the Saturn V, being Vanguard the first and by far most expensive launch system, and then the two recent Falcons, of which it is worth mentioning the comparison that Shuttle's launch cost was about 20 times that of the Falcon 9 and about 40 times that of the Falcon Heavy [30].

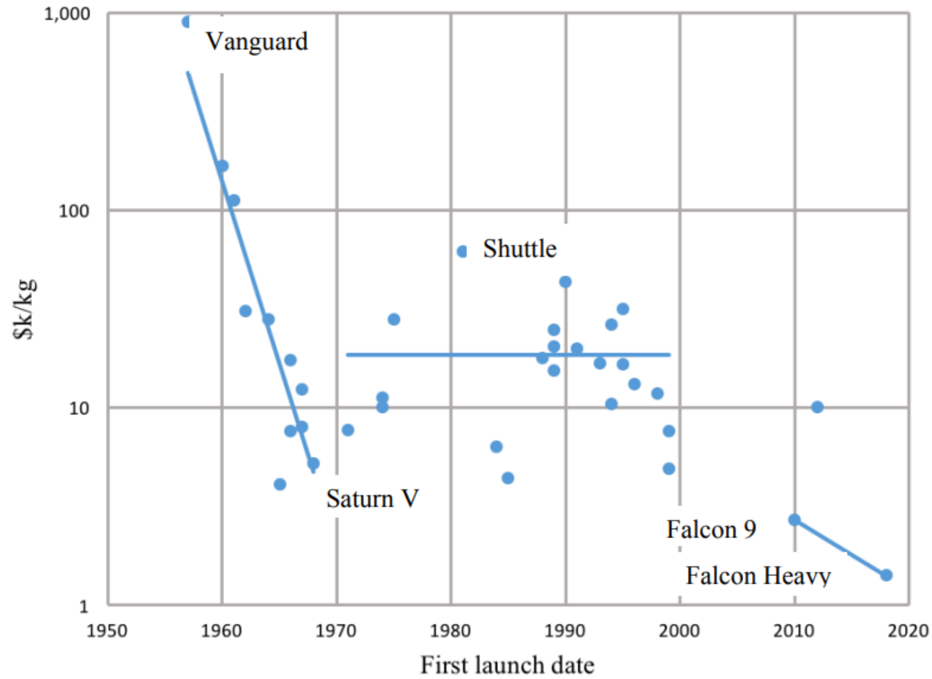

Figure 1.3: Cost of launch to space by cost per kg to LEO. [30]

This tremendous growth of the industry has many positive aspects, but at the same time, it creates new challenges that need to be overcome to get the public support that will be necessary to carry out missions of longer duration or of greater scientific interest, such as reaching Mars. One of these challenges is rocket engine emissions because as launches increase, more emissions are produced. Hence, we need to be able to prove or see how this uptick in significant launches and rocket emissions won't negatively affect the Earth.

The atmospheric effects of rocket emissions depend on the type of propellant (liquid, solid, or hybrid). The most common gaseous emissions are water vapor, black carbon, and carbon dioxide from liquid and solid fuels, as well as hydrochloric acid from only solid fuels [49]. In this work, besides comparing the different emissions of these types of propellants, emphasis will also be placed on the study of the impact of emissions from rockets using methalox (liquid methane-oxygen) as propellant because it is a new propellant and it has never been the focus of models of ozone depletion or changes in atmospheric radiation. Methane-fueled engines can be expected to emit, uniquely, potentially significant amounts of hydrogen oxide (HO_x) into the stratosphere [44].

On the other hand, it will be analyzed how are rocket emissions currently regulated; historically, these impacts have been seen as small and so have escaped regulatory attention [30] and it's interestingly enough, none of the private space companies are lobbying against climate change policy.

Finally, possible ways to mitigate these effects of rocket engine emissions will be analyzed by evaluating the impact of emissions from rockets using methalox (liquid methane-oxygen) as a propellant and establishing solutions that contribute to the reduction of pollutant emissions according to the literature review.

Chapter 2

Problem Statement

The space industry is considered to be one of the fastest-growing industries in the world today, with some sources stating that the space market will increase eightfold in the next three decades. This growth is linked to the number of space rocket launches, which are currently the only means of placing payloads into different orbits in space. However, emissions and climate change caused by rockets are not yet a priority issue for the scientific community, since historically the effects of rocket emissions have been considered small, and the first studies on the subject took place 40 years after the first space launches, and today the literature is not very extensive on this topic.

With the rapid growth of the space industry, and the emergence of space tourism, rocket exhaust gases are accumulating in the atmosphere more than ever. Therefore, the effects of this gas accumulation on the earth need to be studied, as well as how polluting the launch, test, and re-entry phases of spacecraft are. Rocket engine emissions will always depend on the type of propellant being used, so the emissions of liquid, solid, and hybrid propellants will be studied, taking into account different scenarios for the number of launches in the future, among other aspects that will be established to answer the following questions: How much do space rockets pollute, what is the effect and impact of the polluting gases they generate, how are these emissions regulated and how can these impacts on the environment be mitigated?

2.1 Objectives

2.1.1 General Objective

Study the environmental impact on the atmosphere of rocket engine emissions during launch, flight, and re-entry.

2.1.2 Specific Objectives

- Estimate and determine how and how much rocket emissions currently contribute to climate change.
- Assess the impact of emissions from rockets using methalox (liquid methane-oxygen) as a propellant.
- Analyze existing regulations on rocket emissions.
- Establish solutions that contribute to the reduction of pollutant emissions.

2.2 Justification

The main reason why space rockets are becoming more efficient is technology and cost reduction, but not because of the search to reduce emissions. On the other hand, the need to study unexplored regions of space has brought with it the development of giant rockets called "super heavy", likewise investment in the space industry has been growing and this is reflected in the number of launches made each year. Likewise, the emission and accumulation of polluting gases from rockets is directly proportional, and it is becoming increasingly necessary to study the effects of these gases on the different layers of the atmosphere, as this environmental impact assessment is and will be an integral part of launch operations, engine design, among others.

Thanks to multiple applications of space technologies, people's lives on Earth have improved, and to continue to make progress, it is necessary to demonstrate that the growth of the space industry will not significantly affect the Earth. This is done by showing alternatives for reducing and assessing the environmental impact of new fuels.

Chapter 3

State of the Art

Climate change is only getting worse every day, and rocket emissions' effects on climate have only been studied since the late 1990s [44]; 40 years after the first rockets launched satellites into space. Rocket emissions have never been a priority for the scientific community. The literature is sparse and the present state of understanding of rocket emissions is weak [44].

Figure 3.1 shows that since the 1990s the number of publications has increased, with the highest peaks in the graph coming after this period. However, it is interesting to observe the current interest in this issue. There is a high possibility that it will grow as time goes by, as global organizations try to save the environment by finding solutions to the effects of pollutant gases on it. Thus, although research began to be published long after the first rocket launches, the figure shows that there is currently a great deal of interest in analyzing how these emissions can affect the atmosphere and the health of planet Earth.

One of the most important characteristics of rocket engines is the thrust-to-weight ratio, since this parameter determines the efficiency of the vehicle's acceleration, as well as the advantage of not having an altitude limitation, which is important for space applications.

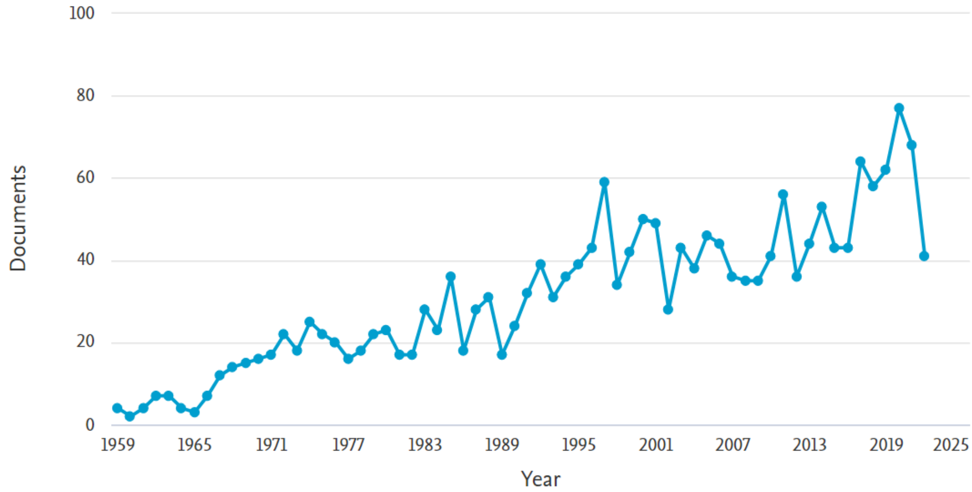

Figure 3.1: Number of publications vs year

Figure 3.2 shows a positive factor for the research, as each of the countries in the chart has its Space Agency, which means that all major space agencies have researched the subject trying to understand the impact of rocket engine gases, analyzing ways to reduce them and new technologies.

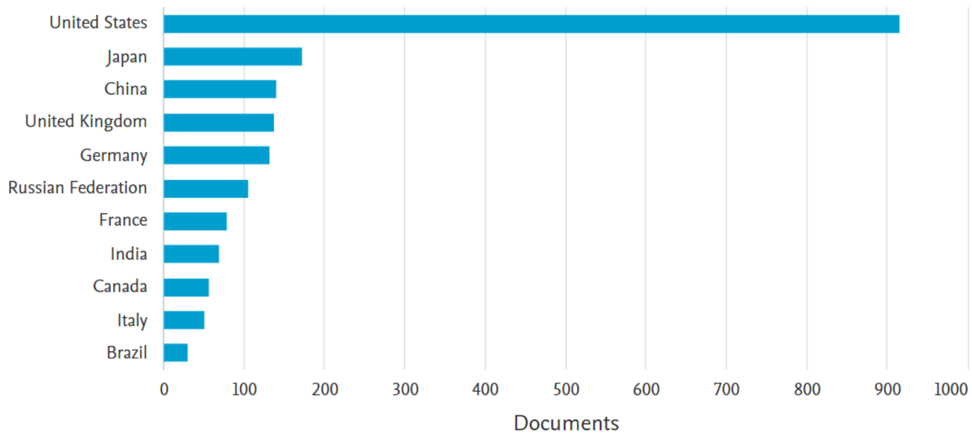

Figure 3.2: Number of publications per country

3.1 Theorical Framework

This section will introduce concepts the reader should know to understand the ideas discussed in the following chapters.

3.1.1 Rocket Engine

The rocket engine is a type of jet engine that generates thrust due to the expulsion of gases at high speed, in the opposite direction of motion, according to Newton's third law. There are several ways to classify rocket engines, one of them is by the type of propulsion that can be used, among this type of classification we find chemical, electric, and solar propulsion engines, among others. [59]. However, this work will be based on chemical rocket engine applications, so the properties and characteristics throughout the paper are documented for this type of rocket engine that is distinguished from other jet engines by its high efficiency, its thrust-to-weight ratio, and other characteristics shown in Table 3.1 that make it the most viable engine for use in space vehicles.

Table 3.1: *Comparison of Some Characteristics of Typical Jet Engines. Adapted from [59]*

Feature	**Chemical Rocket Engine**	**Turbojet Engine**	**Ramjet Engine**
Thrust-to-weight ratio	75:1	5:1	7:1
Specific thrust (N/m^2)	5000-25000	2500	2700
Thrust change with altitude	Slight increase	Decreases	Decreases
Altitude limitation	None	14,000–17,000 m	45000 at Mach 12

According to Table 1, one of the characteristics that allow the use of chemical rocket engines as space launch vehicles is that they have no altitude limit. They can fly at any altitude without performance restrictions. On the other hand, the thrust-to-weight ratio of chemical rocket engines shows a great comparison in terms of the acceleration they can reach equivalent to 15 times the acceleration of turbojet engines, which is a huge advantage due to the long distances that are necessary and the escape velocities of different orbital bodies.

Chemical propulsion is the most used to date. The principle of operation is based on how combustion is carried out. This type of engine requires a fuel and an oxidizer (together called propellant) to achieve the chemical reaction that produces a high pressure and high temperature gas that is expanded through the nozzle causing an exhaust jet at high speed. Chemical propulsion can be classified into:

- Liquid Propulsion: According to [34], this type of propulsion system is the most used for a rocket engine when high levels of specific impulse and thrust are required. In this type of propulsion, the oxidizer and the fuel are usually in different tanks, and then they are sent through a pump to the combustion chamber where, when in contact with the ignition flame, the chemical reaction takes place, figure 3.3 shows the basic configuration of this type of propulsion. There are different combinations of fuel-oxidant, among the best known are liquid hydrogen-liquid oxygen, and RP1-liquid oxygen, among others, however, it is worth mentioning that there are also monopropellant engines, i.e. that only use a tank with the propellant already mixed, for example, hydrazine [59].

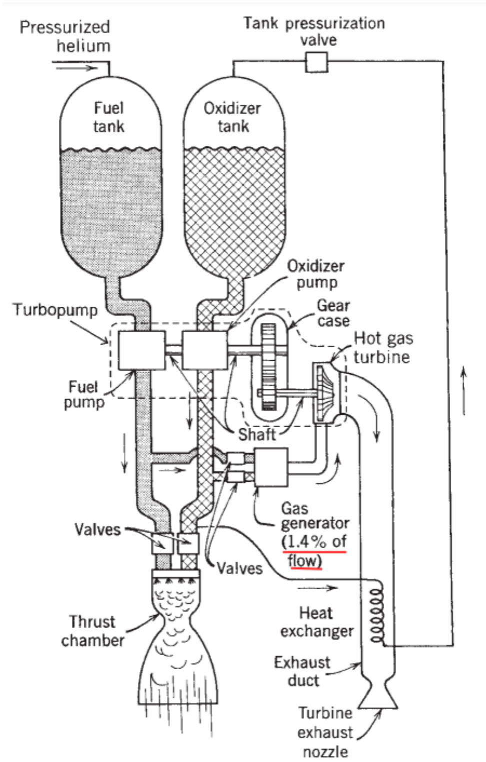

Figure 3.3: Liquid propulsion configuration. From [59]

Hypergolic propellants are part of liquid propulsion and are characterized by the fact that the fuel and the oxidant ignite on contact, without the need for an ignition system, which makes this its main advantage since not having an ignition type makes it more reliable and simple. One of the most widely used hypergolic propellants is a mixture of hydrazine and nitrogen oxide [43].

- Solid Propulsion: In this type of propulsion, the propellant is called "grain", which is a solid mixture of fuel and oxidizer. Solid rocket motors (SRM) usually have few moving parts, and their operation is based on the generation of a spark using an electrical signal that causes the propellant grain to burn, which produces hot gases, a principle that allows these engines to operate in a vacuum. Compared to other types of chemical rocket engines, these are economical, reliable, and simple. Hence, these engines find a wide range of both civilian and military applications [36]. Figure 3.4 shows the major components: a combustion chamber, an igniter, and a nozzle.

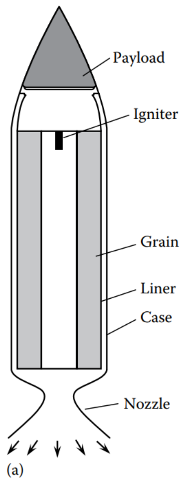

Figure 3.4: Solid rocket engine configuration. From [36]

The most widely used solid rocket propellant for space applications consists of ammonium perchlorate composite propellant (APCP) (70%), aluminium (16%) and binder (14%) [60] and others like hydroxyl-terminated polybutadiene (HTPB). Some solid-fuelled rockets are listed in the APPENDIX A.

- Hybrid Propulsion: This type of engine combines the advantages of liquid and solid propellants, i.e., they can use solid fuel and liquid oxidant, or vice versa, because of this, their propellants are stored in different tanks. Figure 3.5 shows the basic configuration of this type of engine, where it can be seen that the oxidant is injected into the combustion chamber, where the fuel is. The combustion chamber may consist of one or several axial combustion ports in which the fuel is vaporized and combustion begins. An afterburner chamber is usually added at the end of the ports, which ensures that all the fuel reacts with the oxidant before exiting the nozzle [54], the main advantage of these engines is safety.

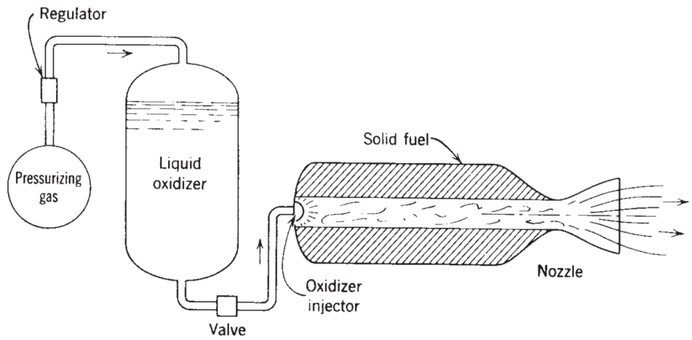

Figure 3.5: Hybrid rocket engine configuration. From [59]

3.1.2 Earth's Atmosphere

The different divisions of the earth's atmosphere will be discussed during the work since rocket engine emissions are usually concentrated in certain specific parts (mostly in the stratospheric zone [44]) and can alter the effect of these emissions. Figure 3.6 shows the different divisions of the atmosphere and the corresponding altitudes.

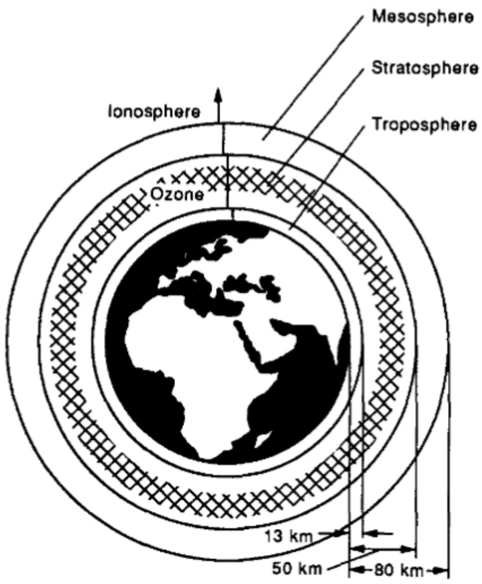

Figure 3.6: Schematic diagram of the Earth's atmosphere. From [6]

Earth's Atmosphere with Rocket Engine Emissions

The purpose of this section is to explain how global rocket emissions affect different zones of the atmosphere, showing which are most affected. In general terms, rocket emissions affect the atmosphere in two ways [44]: many of the chemical reactions that occur deteriorate the ozone layer, and on the other hand, the particles emitted from the engines in the stratosphere induce the phenomenon of radiative forcing which generates

a warming of this area of the atmosphere and a cooling of the earth's surface. Such temperature changes also deteriorate the ozone layer [3].
- **Troposphere**: In this zone of the atmosphere up to 13 km altitude, the only concern is air quality at the launch and landing sites; however, an increase in the amount of water vapor, see section 5.1.1, can warm this region and cool the surface.
- **Stratosphere**: This region is important because it contains the ozone layer and also the particles that are injected in this zone can remain for several years [44], therefore it is the zone that has more studies in terms of emissions, and in that way, this work will focus the emissions. In addition, according to [48] rocket engines constrained to operate only in the troposphere also have negligible climate impact.
The accumulation in the stratosphere of Black Carbon (BC, or soot) particles, see section 5.1.2 and alumina particles, see section 5.2 has several environmental impacts in some scenarios. On the one hand, BC particles intercept a part of the sunlight, transferring heat to the surrounding stratosphere and cooling the Earth's surface. On the other hand, alumina particles reflect sunlight to space, further cooling the Earth's surface which may seem beneficial, however the BC and alumina accumulation layers harm the ozone layer [44].
- **Mesosphere**: Rocket exhaust plumes increase water vapor concentrations in this zone, potentially leading to the formation of mesospheric clouds at 80- to 90-kilometer altitude [62]. On the other hand, NO_x is also created in the mesosphere due to the heat produced during rocket reentry [33].
The following figure shows a rocket launch and its trajectory through the different layers of the atmosphere with the respective environmental impacts it may have on each of them.

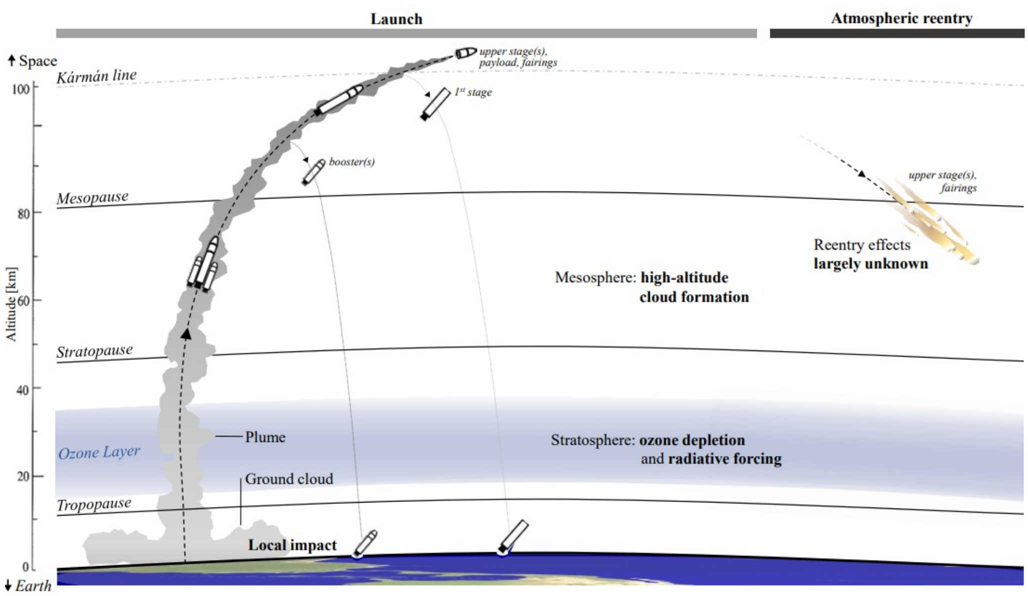

Figure 3.7: Environmental impacts of a rocket emissions through different layers of the atmosphere. From [57]

3.1.3 Radiative Forcing

Radiative forcing is a phenomenon that happens when the amount of energy in form of solar radiation that enters the Earth's atmosphere is different from the amount of energy that leaves. If more radiation is entering Earth than leaving—as is happening today—then the atmosphere will warm up. This is called radiative forcing because the difference in energy can force changes in the Earth's climate [21]. This event is of importance for the work presented here, since each of the different types of and propellent types represents a sum factor for radiative forcing, which is measured in W/m^2, and calculated differently for each emission-propellant type according to its radiative behavior in the atmosphere. However, for this work we are going to make use of the method described in [48], where RF is determined using a mass-specific scattering or absorption factor (m^2/kg), this model also assumes that scattering and absorption are separable into SW (shortwave) and LW (longwave) band components, as for incoming and outgoing flows. A parameter M is called the steady-state mass burden, and is defined by the equation 3.1.3:

$$M = \frac{2}{3} PN10^3 EI(c)\tau \tag{3.0}$$

Where P is the total mass of propellant consumed per launch (e.g. all stages), N is the annual launch rate, and EI(c) is the EI (emission index) of the exhaust product c. The parameter τ is the lifetime of the stratospheric air before it is directed into the troposphere, which has a range between 3-5 years; the model used in [48] obeys for a τ value of 4 years, and the factor 10₃ converts g to kg. The 2/3 factor takes into account typical launches in which about two-thirds of a rocket's total propellant burn (all stages, up to orbit) takes place above the tropopause [48].

In that way, in the general case, for a particular component, the instantaneous RF is given by:

$$RF = (\int I(\lambda)_{LW}\sigma_a(\lambda)_{LW} - \int I(\lambda)_{SW}\sigma_s(\lambda)_{SW})MA^{-1} \tag{3.0}$$

Where σ_a and σ_s are the wavelength-dependent mass-specific absorption and scattering coefficients, respectively. The fluxes $I(\lambda)_{LW}$ and $I(\lambda)_{SW}$ are the mean (global and temporal) solar SW and terrestrial LW flux spectra, respectively. For CO_2, H_2O, and BC we use the integrated fluxes I_{LW} or I_{SW} equal to 235 and 342 Wm^{-2}, respectively, and A is the surface area of the accumulation region equal to $1,2x10^{14}m^2$ [48].

Figure 3.8, shows the atmosphere RF for a fleet of rockets similar to the global fleet used in 2014 [48], showing the relative RF for the various rocket propellant types.

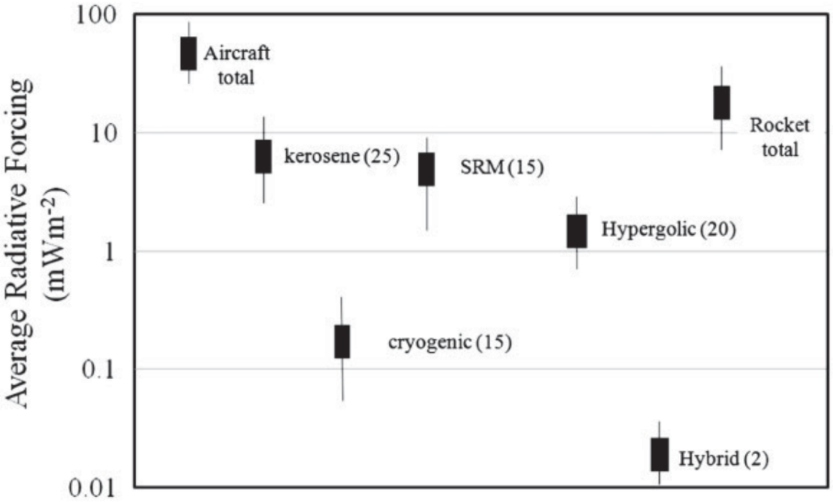

Figure 3.8: Estimated RF for a global fleet of rockets. The numbers in parentheses are launch rates/year. Best estimate of total rocket forcing is 16 mW m2. (Results reported about the amount contributed by each of the emissions of the different types of propellants are shown in Table 17.). From [48]

3.1.4 Ozone Deplection

This phenomenon is related to the so-called "ozone layer" which is a region of the Earth's atmosphere, specifically located in the stratosphere, where there is a high concentration of ozone (O_3) that absorbs much of the ultraviolet sunlight, preventing it from reaching the Earth's surface because it can cause skin diseases in humans. However, some reactions can cause the deterioration of this ozone layer, which can be natural or man-made. Emissions from rocket launches could have ozone-depleting chemicals (ODCs) or substances (ODSs) that contribute to ozone depletion [14], as rockets have different propellants, each of them may have components that contribute more or less to ozone depletion, and these components will be evaluated in this work.

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Chapter 4

Methodology

Research for this work was carried out by utilizing the available literature, and by undergoing two fundamental research phases: The first was to study the emissions and the impact in the atmosphere-specifically in the stratosphere- generated by the three types of propellants used in the industry: liquids (including hypergolic), solids, and hybrids. For this purpose, specific propellants were established for each type, taking into account which are the most used in the industry. For liquid propellants, the study of the emissions of LH_2/LO_x, RP1/LO_x, LCH_4/LO_x, HTPB for solid propellants, and for hybrid propellants, the impact of two propellants was studied. nylon/N_2O and HTPB/N_2O.
Before moving on to the next phase, we analyzed and studied how emissions from phase one are being controlled, including how international organizations are assessing environmental impact. It was found that there is little information available on how they are being regulated; given that the contribution to damage is considered low today, there is very limited information available; so, it has been decided to investigate and show how in future developments and treaties such emissions can be regulated to prevent environmental tragedies.
The second phase of the work was to define launch scenarios to determine how the emissions encountered would behave in the future. The scenario analysis method allows, in the conditions of scarce and uncertain information, to carry out alternative analyses, and at the organizational level would allow further support or evaluation decisions to ensure environmental safety in terms of space activity generated by rocket launches. It also contributes to providing more support to the information and results found in the scenario [12].
To establish the scenarios to be studied, we first studied whether the rocket launching site would have an impact on the amount or form of impact on the environment. Since no information was found in this regard, the launch site was not considered. Thus, three scenarios were analyzed: (a) 134, (b) 400, and (c) 1000 launches per year, taking them into account also at 5 and 10 years. On the other hand, only three types of propellant

will be evaluated in the proposed scenarios, RP1/LO_x (currently the most used), hybrid (this type of propellant will be used for space tourism vehicles), and LCH_4/LO_x (as will be described later, this propellant is expected to be widely used in the future), [44] claims that hydrogen-fueled launch vehicles could launch at any rate possible without the risk of regulatory attention since their emissions are almost entirely water vapor.

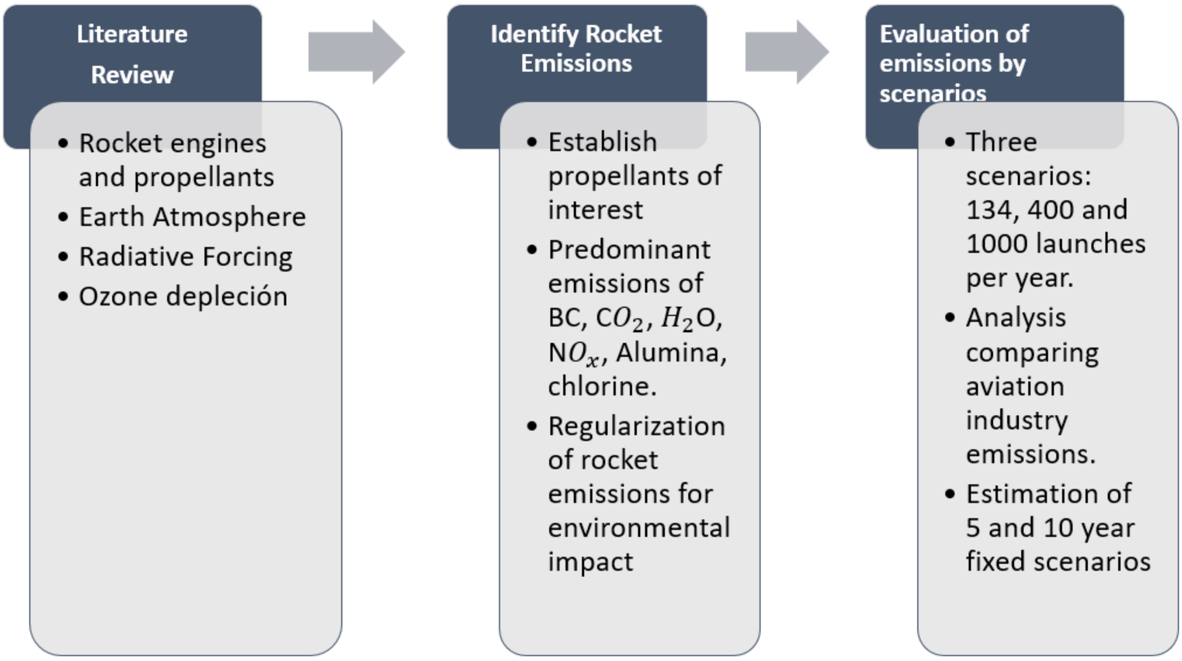

Figure 4.1: Diagram representing the methodology to be carried out and the main points of the work.

Chapter 5

Rocket Emissions

This chapter will present and analyze the emissions and impact generated by the different types of propellants (liquid, solid, hybrid). Furthermore, this part is also dedicated to accomplishing the objective of estimating and determining how and how much rocket emissions currently contribute to climate change during the phases of space flight (launch, flight and reentry).

5.1 Liquid Propellant Emissions

According to the information available in the literature, the liquid propellants to be evaluated will be LH_2/LO_x, RP1/LO_x and hypergolic propellants. (Another propellant that will be analyzed is liquid oxygen + liquid methane, but it will be analyzed in another section.)

5.1.1 LH_2/LO_x:

The use of liquid hydrogen-liquid oxygen as a propellant has been the most used throughout history, used in rockets such as Ariane 5, STS, and New Origin (Blue Origin), among others. Its wide use is due to advantages such as higher specific impulse compared to other propellants, its low molecular weight, and the possibility of manufacturing on Mars, among others.

Liquid hydrogen makes this propellant the friendliest propellant, due to the absence of CO_2 [26], the main emission from LH_2/LO_x is water vapor [14] which is not toxic to human health.

Water vapor

This emission is generated whenever the combustion elements contain hydrogen, as described in section 3.1.2.1, the location of where the emissions are generated is important, for the case of water vapor, the most critical case is when they are generated in the stratosphere because it has a longer lifetime [17].Moreover, the injection of water vapor into the atmosphere produces the formation of ice clouds that are also called polar mesospheric clouds (PMCs) [58].

Figure 5.1, shows the amount of water vapor generated in the stratosphere by global launches, in the period from 1985 to 2013, comparing the USA, USAF (United States Air Force), and worldwide. It is remarkable that the largest contributor of water vapor in this period was USA, and taking into account the information in Appendix A, it can be said that the launch vehicles that most influenced this emission were the Space Shuttle and Ariane 5.

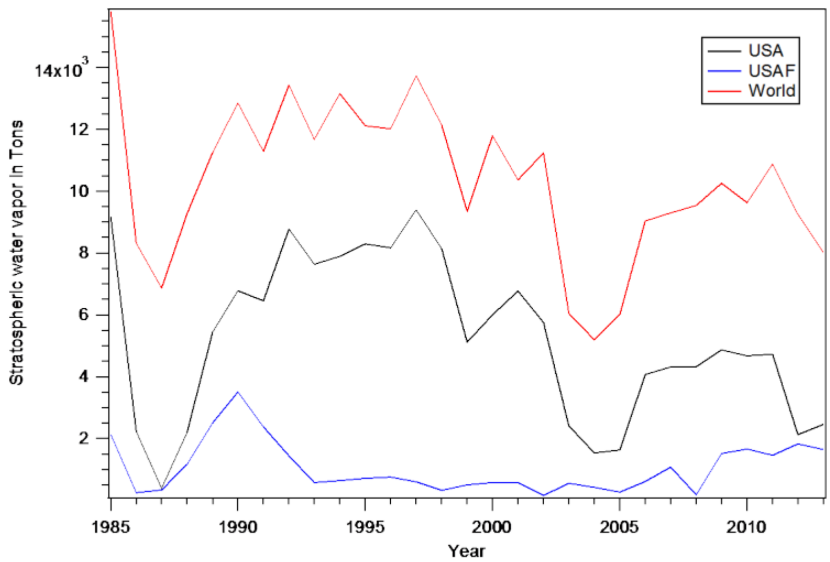

Figure 5.1: Total stratospheric water vapor emissions worldwide from launch vehicles. From [17]

As mentioned in previous sections, each of the different emissions produces radiative forcing to the earth. According to [48], the way to estimate the RF for water vapor is by:

$$\mathrm{RF}_{\mathrm{H_2O}} = \sigma_{\mathrm{H_2O}} I_{\mathrm{LW}} M_{\mathrm{H_2O}} A^{-1} \tag{5.0}$$

Where $\sigma_{\mathrm{H_2O}}$ is now the mass-specific cross section for H_2O, M_{H_2O} is the stratospheric H_2O burden, and A is described in section 3.1.3 [48]. According to the same reference, cryogenic propellants, such as LH_2/LO_x, produce an $\mathrm{RF}_{\mathrm{H_2O}}$ of 0,02 mW/m^2.

Nitrogen oxide (NO_x)

Another emission found in the literature produced by rocket engines using LH_2/LO_x is NO_x, which source comes mainly from afterburning, which occurs in essentially all rocket plumes in the lower stratosphere [9], NO_x is emitted in both fuel burn and reentry of the spacecraft due to the heat of the surrounding air and the generation of shock waves during this phase [51], this emission also contributes to the loss of the boundary layer and is generated in the mesosphere and stratosphere during spacecraft reentry [33]. Regarding NO_x emissions:

• Considering the data in APPENDIX A, for rockets using LH_2/LO_x as propellant, the mass range of NO_x (in tons) generated is between 0.01 and 1.99.

• As for reentry NO_x emissions, [20] estimated that the NO_x produced during a Space Shuttle reentry is 17.5±5.3 of the spacecraft mass, with a peak emission at 68 km.

• While LH_2/LO_x rocket exhaust contains NO_x and H_2O, which do result in ozone loss, it is typically used for the upper stages of rockets, and this propellant is often burnt at higher altitudes than the ozone layer [51].

• According to [48], the amount of NO_x produced compared to other emissions is small and does not cause significant RF radiative forcing directly, however, it can produce it indirectly [27], considering a positive RF due to the reaction in the stratosphere with CH_4 (methane).

5.1.2 RP1/LO_x

This propellant is a mixture of RP1 (Rocket Propellant) - which is a highly refined form of kerosene - and liquid oxygen as an oxidizer. It is commonly preferred because it has a higher density than LH_2/LO_x, thus allowing for smaller propellant storage tanks and making it an easier propellant to work with. Some launch vehicles that have used and continue to use this substance as propellant are shown in APPENDIX A, where it is worth mentioning the Falcon 9 and Falcon Heavy, since it is the rocket family that currently has the highest launch frequency [7], as can also be seen in the Figure 5.2.

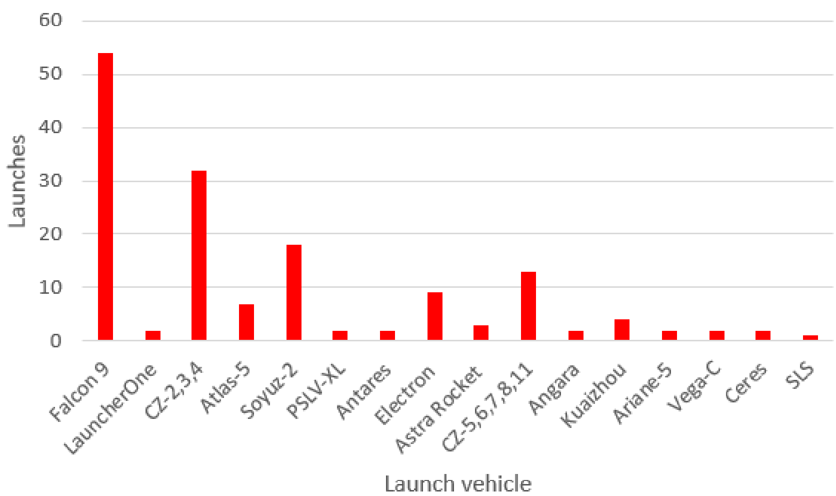

Figure 5.2: Orbital launches in 2022 by launch vehicle family: Adopted from [32]

Based on information provided in SpaceX 2007, exhaust from the Merlin engines (of Falcon 9) consists mainly of CO_2, CO, hydrogen, NO_x, and water vapor [1] and [14]¨ adds BC (or soot) emissions.

Carbon monoxide (CO)

According to the same reference, [1], the estimated amount of CO per launch is 95.22 tons. However, that amount is emitted above altitude (3000ft) where air quality may be impaired, and then, although it may be seen as a threat in the other regions of the atmosphere, most CO emissions are rapidly oxidized to CO_2 which, if true, would mitigate the harm [37], and that is why only CO_2 emissions in the stratosphere will be considered.

Carbon dioxide (CO_2)

The lifetime of these emissions in the atmosphere is in the range of 175-250 years [4], which means that CO_2 particles emitted since the first launch of the first rocket are still circulating in the atmosphere today. CO_2 is a component that contributes to the effect of radiative forcing, so according to the method in [48], it can be estimated by:

$$RF_{CO_2} = I_{LW}\sigma_{CO_2}(\bar{M}_{CO_2} + NM_{CO_2})A_E^{-1} \tag{5.0}$$

Where σ_{CO2} is the mass-specific absorption coefficient; $\bar{M}_{CO_2}$ equals the accumulated CO_2 burden from all rockets into all parts of the atmosphere since the start of the space age; M_{CO2} is the annual CO_2 emission by rockets; N is the number of years from 2013, accounting for future launches; and A_E is the solar illuminated area of the surface of the Earth [48]. The results obtained concluded that the RF generated by CO_2 emissions from a single launch vehicle using RP1/LO_x as a propellant is equivalent to $6x10^{-6}mW/m^2$ insignificant within the context of global climate change.

One of the reasons for the increased interest in the impact of rocket engine emissions on the atmosphere is the inclusion of the new "space tourism" market, which, as shown in Figure 5.3 in terms of revenues expected, has had and is expected to increase greatly. [22] determined that one passenger on a suborbital space tourism flight emits approximately three-quarters of a ton of CO_2, equivalent to on a round trip aircraft flight between Los Angeles and London.However, However, as the number of space tourism-related launches is set to increase, such CO_2 emissions are expected to be directly proportional.

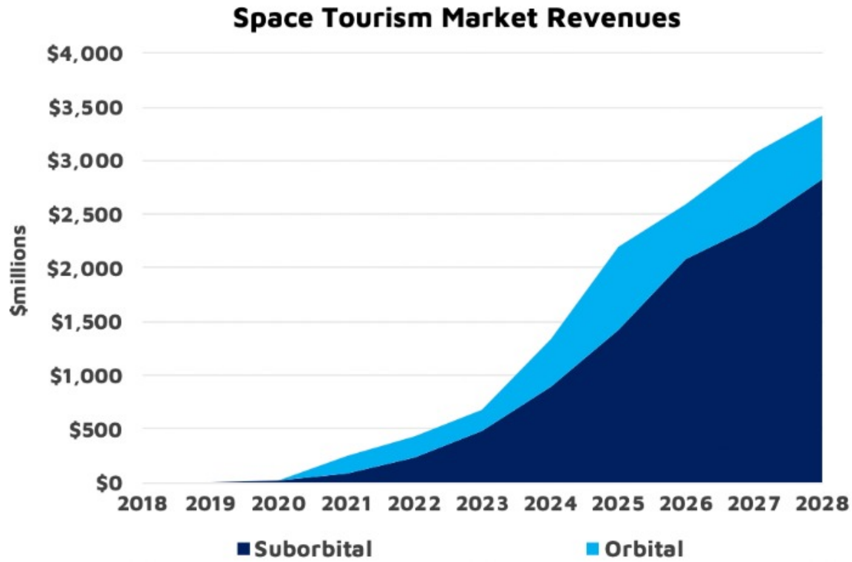

Figure 5.3: Space Tourism Market From [25]

On the other hand, [40], determines that for an orbital flight to the ISS using the Soyuz vehicle -which uses RP1/LO_x as propellant-, the amount of emissions generated per passenger is 143 tons, that is, with a crew of three passengers would generate 429 tons. Assuming 50 trips per year with this vehicle to the ISS would produce 21450 tons of CO_2, which would be 0.068% of the CO_2 emissions released by United Airlines as reported in [5] equal to 31.3 million tons in 2013. Likewise, comparing the CO_2 emissions of the Falcon 9 vehicle taking into account the same conditions described above, this rocket generates 341.60 tons of CO_2 per launch, which translates to 17080 per 50 launches per year, this analysis is shown in Figure **??**. A similar comparative analysis can be made with the CO_2 aircraft emissions reported in 2020 [19] equivalent to 122 million metric tons contrasted with the emissions of the Falcon 9 Heavy rocket that produces 976 metric tons [19], so, for this vehicle to produce similar amounts of CO_2 it would have to perform more than 123,000 launches per year.

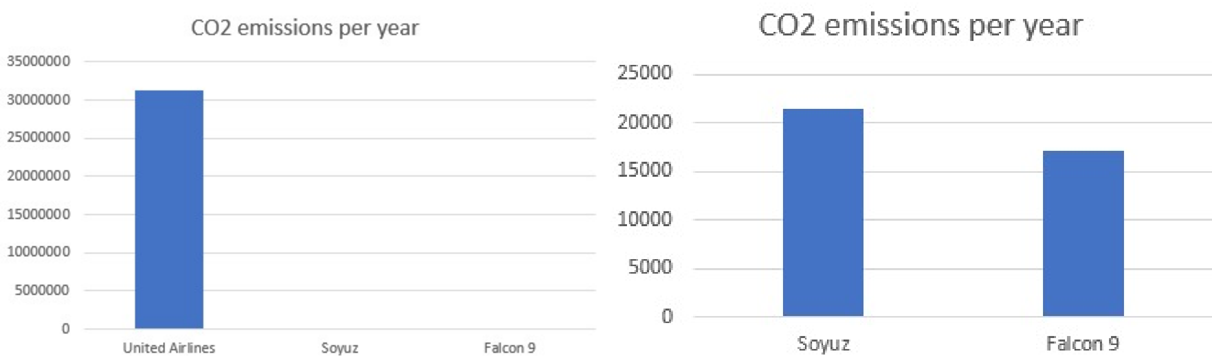

Figure 5.4: CO_2 emission analysis for different vehicles.

• In order to compare results, [52] determined that the CO_2 emission is 0.222 kg per kilogram of propellant burned. Such a result can be used to analyze any type of mission, determining the amount of propellant needed for it.

Black Carbon (BC)

The combustion of RP-1 causes the emission of black carbon, which, as will be demonstrated, is the product that contributes the most to radiative forcing due to the absorption of solar flux caused by the long BC lifetime in the stratosphere, and on the other hand BC contributes to global warming [52].
The following equation is used to estimate the RF of BC emissions:

$$\mathrm{RF}_{BC} = \sigma_{BC} I_{\mathrm{SW}} M_{BC} A^{-1} \tag{5.0}$$

According with the methodology in [48], the specific BC absorption σ_{BC} is assumed like $10^4 m^2/kg$, so, the direct RF produced by BC is equal to 0.32 mW/m^2, having a ratio of approximately 20 grams of BC per kg of propellant (RP1/LO_x), from what can be concluded considering that Falcon 9 uses 395,700 kg of propellant in its first stage, 7,914,000 grams of BC would be generated. Taking into account other literature sources and APPENDIX A, the Falcon Heavy is the largest BC emitter (7.79 metric tons) compared to other rockets in history. Figure 5.5 shows the total BC emissions at specific altitudes based on the different models used for Atlas II rocket estimation, the figure has an origin of 1 g/kg, which is the minimum average estimated in the literature, and 25 g/kg, which is the maximum estimated average [50].

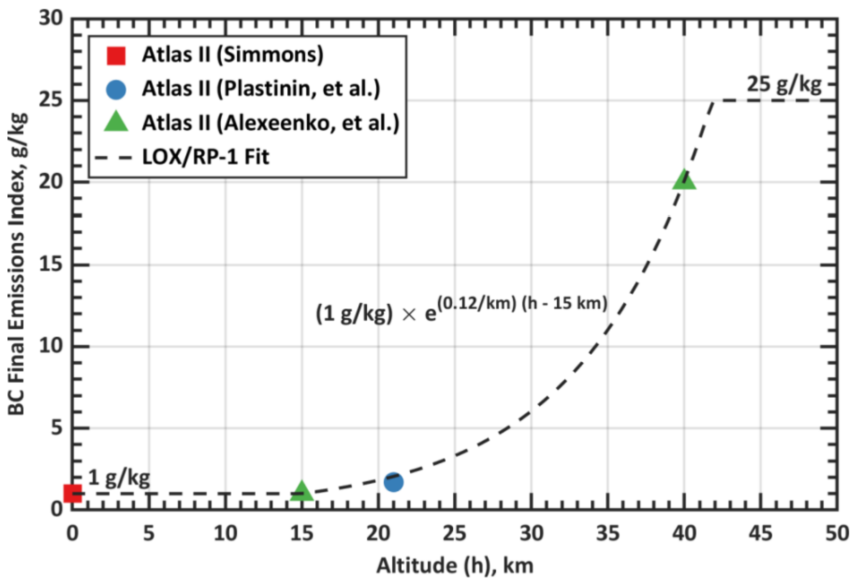

Figure 5.5: Total black carbon (BC) emissions as a function of altitude. From [50]

Nitrogen oxide (NO_x)

This reaction product in rocket engines is given for any type of propellant. However, taking into account APPENDIX A, the average value of NO_x generated by RP1/LO_x is 0.02, so it is considered an emission that has no significant impact on the atmosphere.

5.1.3 Hypergolic Propellants

According to above descriptions, hypergolic propellants are liquid propellants with easy ignition and high toxicity, both to humans and ecosystems. [63]. The hypergolic substance most commonly used as rocket propellant according to the literature is Unsymmetrical dimethylhydrazine (UDMH) commonly called hydrazine, [45, 62, 52], emissions will therefore be analyzed mainly for this hypergolic substance. The combustion emissions from UDMH-fueled rockets are thought to include CO_2,N_2,H_2O,BC and other products that do not contribute significantly to environmental impact, likewise, simplifying the emissions that contribute most to ozone depletion, according to [45], CO_2 and N_2 emissions from UDMH do not affect the stratospheric chemistry and are therefore not considered.
Most Chinese rockets, as can be seen in APPENDIX A, use this UDMH as fuel, mixed with N_2O_4 (nitrogen tetroxide) as an oxidizer. However, [45] carried out a study determining the emissions in the stratosphere of the Russian Proton rocket, which used the propellant described above consuming approximately 750 tons of it per launch, determining that the major component of the emissions would be H_2O equivalent to 350 g per kg of propellant burned. Likewise, [45] states that total UDMH emissions generate 1.8 kg of ozone loss per kg of propellant burned in the stratosphere. Table 5.1 shows the UDMH emissions found in the literature:

Propellant	**CO**	CO_2	H_2O	**H**	**O**	**OH**	N_2	NO_x	**BC**
N_2O_4/UDMH	0.227	0.114	0.258	0.013	0.006	0.020	0.353	0.005	0.004

Table 5.1: Emissions generated by combustion of N_2O_4/UDMH given in kg/kg of propellant burned. Adopted from [52]

As can be seen in the table, the product that generates the most emissions is dinitrogen (N_2) equivalent to 0.353 kg/kg of propellant burned, followed by water vapor emissions equal to 0.258 kg/kg of propellant burned. Thus, taking into account APPENDIX A, the Chinese Long March 4B rocket uses this propellant, at a quantity of 182000 kg in the first stage [1], thus producing 64246 kg of N_2 and 46956 kg of water vapor respectively.
The impact on the ozone layer from H_2O and NO_x emissions from hypergolic engine exhaust was modeled by [45] using the UDMH-fueled Russian rocket Proton, which has been one of the most launched rockets in history, extrapolating that according to the results

[1] "The Annual Compendium of Commercial Space Transportation: 2018"

the ozone loss from rockets using this propellant would be equal to 0.0002% with most of it coming from NO_x products, and likewise, such percentage could represent between 66-90 times less ozone depletion than solid rocket motors [14].

However, the use of these propellants is being reduced due to their toxicity, so much so that [42] conducted a study with 6107 workers in aerospace industries and concluded that exposure to hydrazine in rocket engine work increases the risk of dying from lung cancer, and possibly other cancers, hence new alternatives are expected to emerge that seek to reduce or replace the use of this type of propellants for rocket engine use [2].

5.2 Solid Propellant Emissions

The model used in [48], determined the RF that a launch would generate by analyzing several types of propellants with a mass of 500 tons of propellant, including among them a SRM, the results are shown in Table 5.3. Of interest in this section is the RF equivalent of the SRM equal to 0.285 mW/m^2 from CO_2, H_2O,BC and Al_2O_3. Another product of SRM combustion is chlorine compounds emitted directly into the stratosphere [64], these products contribute to ozone deplection and taking into account the study made in [16], Table 5.2 summarizes the emissions from the Athena 2 rocket, which used HTPB (hydroxyl-terminated polybutadiene) as solid propellant. However, ATCP is known to be the most ozone-harmful solid propellant [52].

Propellant	CO_2	H_2O	Al_2O_4	**HCl**	**NO**
SRM	382	300	362	217	2

Table 5.2: Emissions generated by combustion of SRM (Athena 2 rocket) given in g/kg of propellant burned. Adopted from [16]

		Direct RF at constant launch rate from individual components (mW/m^2)			
Rocket type	**Total Propellant (t)**	CO_2	H_2O	**BC**	Al_2O_3
Kerosene	500	6x10^{-6}	0,005	0,32	-
Cryogenic	500	-	0,02	-	-
SRM	500	2x10^{-6}	0,005	0,1	0,18
Hypergolic	500	1x10^{-6}	0,001	0,06	-
Hybrid	10	3x10^{-8}	6x10^{-5}	0,01	-

Table 5.3: RF emitted by different types of propellant per ejected component.

[2]C. H. McLean et al., "Green Propellant Infusion Mission program overview and status," 2014 IEEE Aerospace Conference, 2014, pp. 1-20, doi: 10.1109/AERO.2014.6836245.

5.2.1 Alumina (Al_2O_3)

Al_2O_3 is one of the most abundant solid propellant combustion products. However, the behavior and how the reaction of this component with the atmosphere impacts ozone loss is still uncertain and poorly understood due to scarce data, which is also highlighted in several studies [53, 64]; however, its behavior is known to be more complex than BC [48]. Table 6 in APPENDIX A shows alumina emissions in tons per launch of some launch vehicles.

This emission is unique to SRM, however, it is a major contributor. It could, depending on launch scenarios, contribute significantly to the environmental impact along with BC emissions that theoretically emit at a reduced rate compared to kerosene engines [48], assuming the same BC emissions value for hypergolic propellants equivalent to 4g/kg. According to [16], SRMs emit a total of 320 grams of alumina per kg of propellant burned. Of particular interest are the small particles (1 μm in diameter) that are left recirculating through the stratosphere, because they have a longer lifetime in the stratosphere, such particles are called "submicron mass fraction" (SMF) and the fraction that meets these criteria has been reported as between 1% and 30% [47].

According to the literature, models were performed to estimate the emissions from SRMs such as the Space Shuttle and Titan IV rocket,[15, 28], where the emission of Al_2O_3 particles into the atmosphere considering nine space shuttle and four Titan IV launches was 3.9 kt (kiloton)/yr, of which 1.12 kt/yr (900 and 220 t/yr from the space shuttle and Titan IV, respectively) are deposited directly to the stratosphere (i.e., above 15 km). From these data, together with Table 3 and the mass of propellant used by each launch vehicle, an approximate model can be estimated to determine the emissions generated by active SRMs -assuming emissions are uniform throughout the year-, which is shown in Chapter 6.

5.2.2 Chlorine (Cl)

Following the literature, during the Climatic Impact Assessment Program by Hoshizaki, 1975, chlorine released from solid-fuel rockets was first noticed as a potential threat to stratospheric ozone. [29], specifying that most chlorine emissions may be in the form of HCl (which does not destroy the ozone layer directly), but at the time of afterburning, the cooling of the exhaust plume may release chlorine in the form of Cl and Cl_2 which immediately begin to deplete the ozone layer [23]. Different studies have been done to determine the amount of chlorine emitted by the Space Shuttle during its active time. Various results of these include:

-As a result of the Space Shuttle solid motors' operation at altitudes between 15 and 45 kilometers, about 70 to 80 tons of chlorine are released [64], which is in agreement with the results of [17] shown in APPENDIX A.
- [10] summarizes the emissions in tons/launch of chlorine from 10 vehicles, of which 9 emit more Cl in the troposphere (0-15km) and a lower percentage in the stratosphere (15-60km), however, the particles emitted in the stratosphere are the cause of ozone depletion. On the other hand, this study coincides with [64], estimating a Cl amount for the Space Shuttle of 79 tons/launch.
- Figure 5.6 shows the total chlorine emissions produced during the period 1991-2009 by nine launch vehicles that were active during that time, launched by USAF (United States Air Force), U.S (United States), ESA (European Space Agency) and the sum around the world. The graph shows an increase in chlorine ejected into the atmosphere over time.

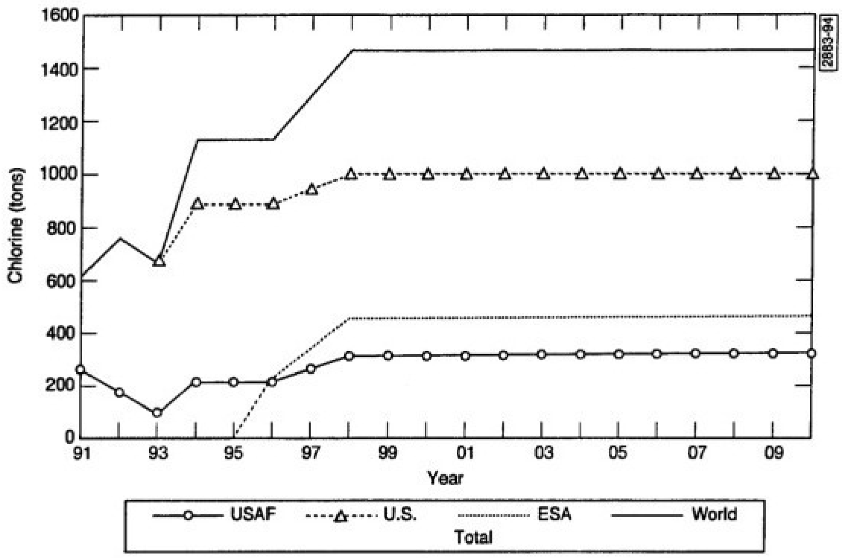

Figure 5.6: Total chlorine emissions in the stratosphere during 1991-2009. From [10]

To compare the emissions of chlorine and alumina, Figure 5.7 shows the number of particles emitted by these two components in tons, for different launch vehicles. The figure shows how the amount of alumina particles exceeds that of chlorine over time.

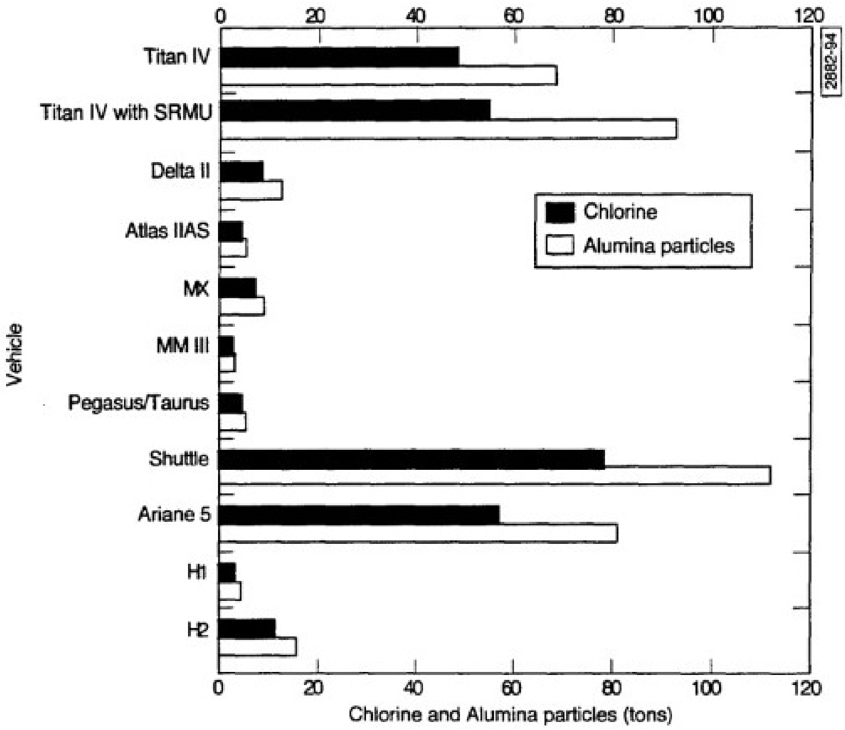

Figure 5.7: Emissions of chlorine and aluminum particles emitted by different launch vehicles. From [10]

5.3 Hybrid Propellant Emissions

For the study of this type of propellant, the emissions will be based on Virgin Galactic's SpaceShipTwo vehicle, which has as propellant two hybrid options: HTPB/N_2O or nylon/N_2O, the first substance being the liquid oxidant and the second one the solid organic material as fuel [13]. A total mass of 15,500 pounds would be used during each launch, consisting of 13,000 pounds of N_2O and 2,500 pounds of solid organic fuel, thus releasing the following quantities and emissions products each launch:

Description	CO_2	**CO**	H_2O	NO_x	N_2	H_2
Emissions per launch						
Using nylon/N_2O	1232	331	1279	28	3944	154
Using HTPB/N_2O	1669	688	695	28	3875	10

Table 5.4: Estimated emissions for hybrid propellants (kg). Adapted from [2]

Emissions shown in Table 5.4 are ejected above the troposphere (¿15 km), as the rocket is carried by aircraft into the lower stratosphere where rocket ignition takes place, thus, emissions during hybrid propellant launch, i.e., below 15 km (troposphere) are equal to 0, and likewise, on reentry, specifically SpaceShipTwo has emissions of 0 due to glide in

this phase of the mission.
BC emissions produced by hybrid propellant engines have not been investigated or measured. However, according to [59] it is expected that BC emissions for hybrid engines will be larger than for kerosene engines because of lower carbon particulate oxidation rates in the hot plume. On the other hand, [46] performed a model assuming a value of 60 g of BC per kg of propellant consumed. This assumption will be taken into account in this study.

Additionally, [48] determines that this type of propellant contributes to radiative forcing via CO_2 and BC, in negligible amounts equivalent to 3x10^{-8} and 0.1 mW/m^2 respectively.

5.4 Liquid Methane-LCH_4

Together with LO_X, this fuel forms a propellant that is attracting significant interest [3], because, despite its disadvantages, it has many advantages, such as its ease of handling compared to liquid hydrogen [38], its higher specific impulse than RP1 [11], and other advantages. One of them stands out in importance for this work and it is regarding the reuse of engines that use this propellant, since methane does not polymerize during engine ignition as kerosene does -that is, it leaves fewer residues-, so it is easier to clean a methalox engine before reusing it [35].
Table 5.5 shows the emissions generated by methane together with liquid oxygen as an oxidant. The data are shown in kg of emissions per kg of propellant consumed, predominantly CO, CO_2 and H_2O products.

Propellant	**CO**	CO_2	H_2O	**H**	**O**	**OH**
LO_X/LCH_4	0.344	0.187	0.422	0.018	0.005	0.024

Table 5.5: Emissions of a methane-lox rocket engine. Adopted from [52]

Emissions of NO_x are not shown in the table above because they are too low, so BC emissions are reported in [50, 18] as 20% of the value for LO_X/RP-1 engines based on the reduction observed for internal combustion engines, in other words, 4 grams of BC were emitted for every kg of propellant emitted. Taking this into account, the launch of the Starship rocket consumes 3700 tons of LCH_4 [52] so, a Starship launch would generate 14800 kg of BC.

5.5 Regularization

The objective of this section is to answer the question of how are these emissions regulated or how are the environmental impact policies of rocket engines being carried out. It is nec-

[3]Companies like Blue Origin and SpaceX have been working on engines using this propellant [35]

essary to study this because throughout the history of the space industry these emissions have been small and therefore have escaped regulatory attention [44]; The rocket industry does not have an international cooperative organization similar to the International Civil Aviation Organization to provide information, guidelines, and regulations. [48]. As a consequence, rocket engine emissions regulations need to be carefully analyzed to ensure they preserve the environment while allowing industry growth.

Several references state that rocket emissions have certain particularities when it comes to regularities, including the fact that it is risky to establish limits or regulations for this industry because it is still uncertain how much environmental damage or ozone depletion they can cause, moreover: (1) The lack of critical impacts to date: rocket launch and re-entry impact assessments currently lack credible scientific assessments, and regulatory agencies have assumed rocket emissions are acceptable or negligible, (2) The atmosphere as a global commons: global emissions mix beyond national borders and widespread impacts are the result of collective actions. The maintenance of a global commons is entirely dependent on widespread international participation, even with sufficient political will at a national level [57], (3) Development of nations: since developed nations have already contributed to the current pollution threat, there could be a debate about whether they have a greater obligation to reduce emissions, whereas countries without even a space agency might have to take on such regulations.
[41] establishes some principles that could be used for the approach of regulations for rocket emissions, among them proposes:

5.5.1 Self-regulation

This principle refers to the fact that the target or organization to be regulated imposes regulations and consequences for not complying with them by itself. This principle could be acceptable because it is not imposing a reduction of launches or a third party forcing compliance with objectives or rules.

5.5.2 Transparency

It refers to the honesty that companies should have when applying principle 5.5.1, on the other hand it mentions that companies should have Monitoring, Reporting and Verification (MRV) mechanisms, the latter being by an independent international entity.

5.5.3 Regional and International Cooperation

Organizations and space agencies must cooperate to regulate rocket emissions, as this facilitates information exchange and prevents duplicate regulation.

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Chapter 6

Model Analysis-Scenarios

[12] notes that due to the lack of information and exact values for analyzing the environmental impact of space activities, an estimation of the situation can be determined through the implementation of various scenarios to predict how the future will unfold for ensuring environmental safety in the context of different launch developments. As described in the methodology of the work, three different rocket launch scenarios will be considered to analyze the behavior of the emissions with three different types of propellants (RP1/LO_x, Hybrid propellants and LCH_4/LO_x).

6.1 Current Launch Scenario

In this scenario, the number of emissions generated by rocket engines will be simulated, if the rate of increase in launches in the world were to remain constant at current levels. To illustrate this, using data from [32]; represented in Figure 6.1, show data on launches from 2010 to 2022, resulting in an increased rate in equation 6.1.

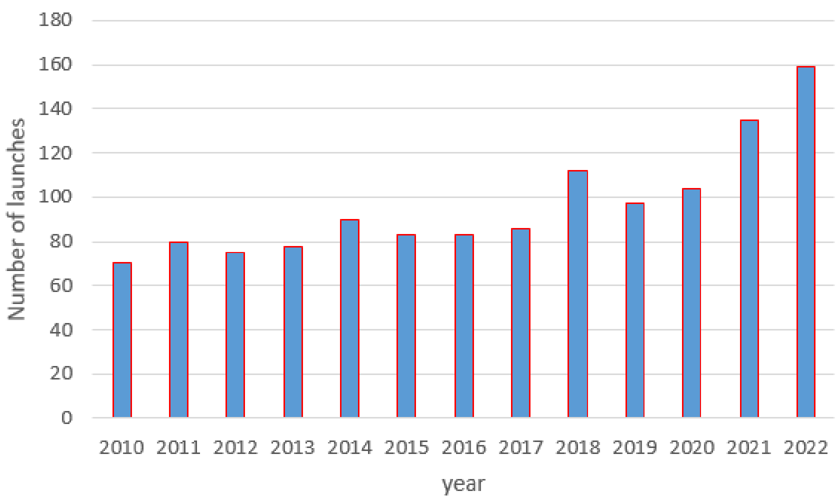

Figure 6.1: Launches per year (2010-2022).Data from [32]

$$\%rate of increase = \frac{|70 - 159|}{159} * 100 = 55.9\% \tag{6.0}$$

In turn, this represents an average of approximately 96 launches per year. Comparing with the literature, [56] determined an increased rate between 2017-2022 time period of 58% along with a Compound Annual Growth Rate (CAGR) of 4.5%; (Figures 6.3,6.4) thus, for better accuracy of the calculations, we will use the results given in that reference. Figure 6.2 shows the estimated number of launches taking into account this percentage increase from 2010 to 2035.

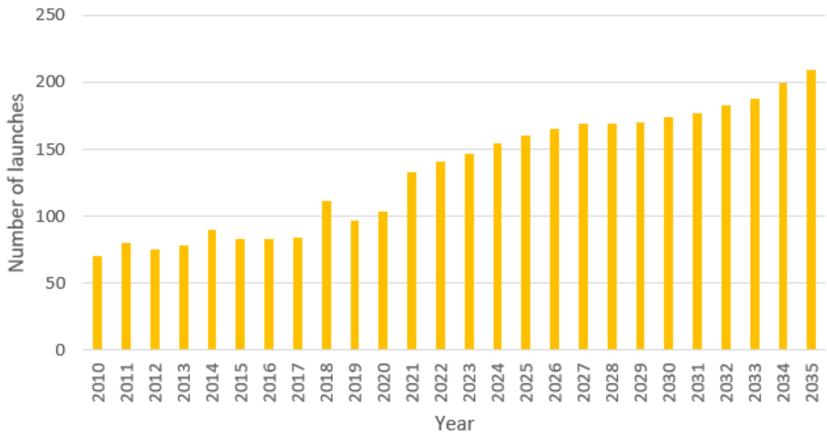

Figure 6.2: Launches per year according to the reference, in the period of (2010-2035).Adopted from [56]

Considering the previous Figure, the average number of launches per year, assuming a constant growth of the current number of launches would be 134; and that will be the number of launches evaluated in this section.

6.1.1 RP1/LO_x

The analysis of emissions from rocket engines using RP1 as propellant will be based on the Falcon 9 launch vehicle, as it is the one for which more information is available. As mentioned in section 5.1.2, the emitting products or products that may have some environmental impact from this vehicle are mainly CO_2 and BC.

As for CO_2, it is known to be a component that contributes to radiative forcing. Taking into account the equivalent presented in previous sections, the RF generated due to CO_2 by 134 launches would be $8.04{\times}10^{-4} mW/m^2$ which represents a much lower percentage compared to the RF from global aviation's total CO_2 emission [8]. On the other hand, according to the amount of tons of CO_2 generated by a Falcon 9 launch, 134 launches per year would generate 45774.4 CO_2 tons, equivalent to 0.14% of the CO_2 emissions released by United Airlines in 2013.

Black carbon (BC) emissions contribute the most to radiative forcing. A scenario of 134 launches per year produces 42.88 mW/m^2. In terms of BC emissions per kg, Falcon 9 produces 395,700 kg of propellant per launch in its first stage, so with a ratio of 20g of BC per kg, 134 launches would generate 1060 tons of BC. According to [31], aircraft emit 0.03 g per kg of fuel burned, and the comparison confirms the claim of [48] that rockets undoubtedly inject more BC into the stratosphere than aircraft.

6.1.2 Hybrid propellants

Evaluating future emissions under different hybrid propellant engine scenarios is of interest because the company that plans to make the most space tourism trips uses hybrid propellants: Virgin Galactic, with the SpaceShipTwo vehicle which has two propellant options as seen in section 5.3; however, the scenario analyses will be calculated using HTBP/N_2O and a propellant quantity of 13,000 pounds (5898 kg). Based on Table 5, which shows the number of emissions per launch, carbon dioxide, and nitrogen dioxide products havee the greatest impact. In addition, a BC emission of 60g/kg propellant resulted in 353.88 tons per launch. Table 6.1 shows the total RF contribution of hybrid propellants, and Table 6.2, illustrates the amount of emissions generated based on 134 launches in a year.

6.1.3 LCH_4/LO_x

The introduction of this new propellant should be analyzed because several companies are planning to use it for launch vehicles, due to its characteristics. For example, SpaceX is using this propellant in the Starship rocket, which is intended to perform different missions including travel to Mars, the Moon, cargo launches, long duration space flights, among others. [56] presents Figures 6.3 and 6.4, two different scenarios respectively. Figure 6.3 represents the case where the launches in the period of 2017-2040 continue to have the same propellants, without any alternative in search of emissions reduction, dominating the use of UDMH/N_2O_4 as it is another type of hybrid propellant that is being implemented in space tourism trips.

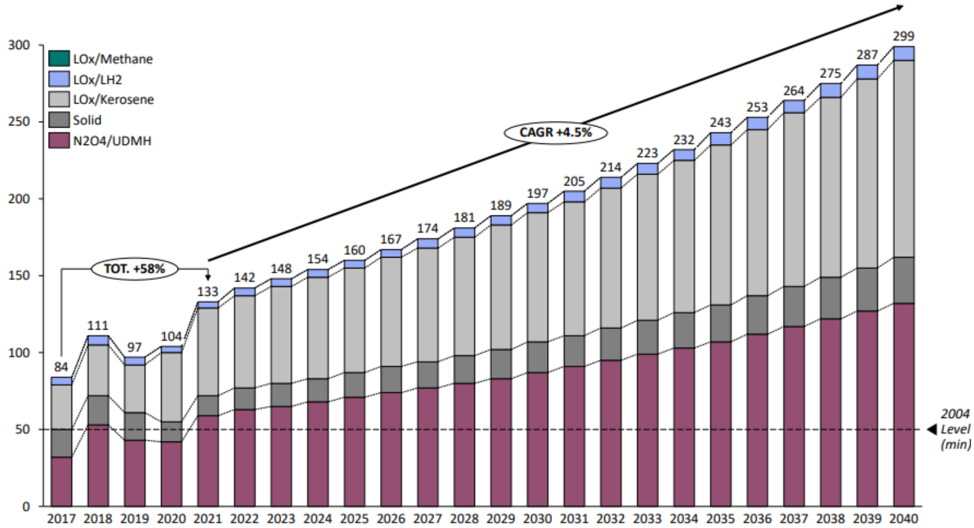

Figure 6.3: Number of launches per year, 2017-2040 using identical propellants currently. From [56]

Figure 6.4, shows how the behavior of launches would be in the same period (2017-2040) but taking into account the use of LCH_4/LO_x; the graph shows that RP1/LO_X is still the preferred propellant for rockets, but it appears that the use of this propellant is beginning to gain traction.

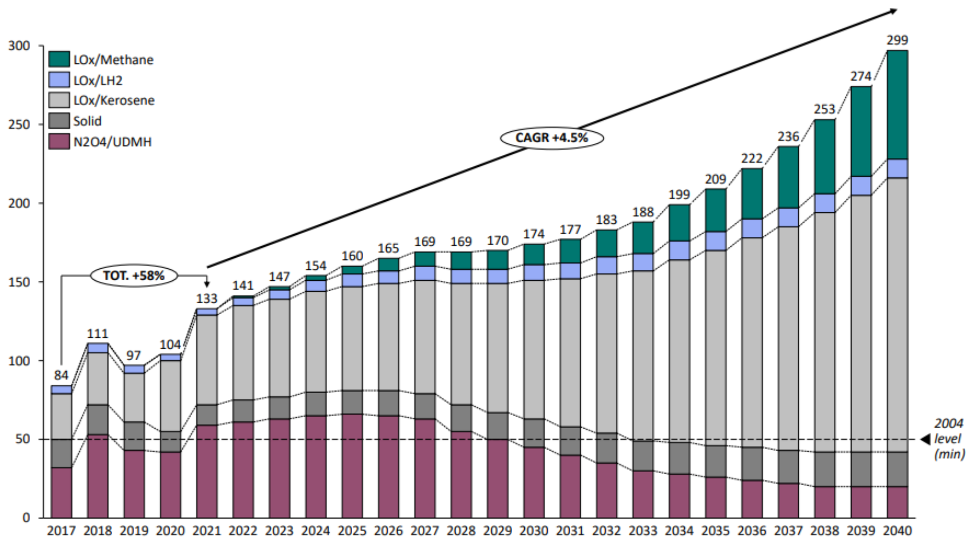

Figure 6.4: Number of launches per year, 2017-2040 taking into account the implementation of LCH_4/LO_x From [56]

As with the previous propellants, the greatest environmental impact is given by carbon oxides and black carbon, the results of which are shown in Tables 6.1 and 6.2, taking into account the amount of propellant consumed by the super-heavy rocket Starship. No useful information was found in this case concerning the RF contribution of this type of propellant.

Propellant	RF Contribution $(mW/\mathbf{m}^2)^a$	***Total 5 years***	***Total 10 years***
RP1$/LO_X$	42.880804	214.4	428.8
Hybrids	13.400402	67	134
LCH_4/LO_X	-		

Table 6.1: Radiative forcing contribution taking into account a 134 vehicle launches scenario.[a] value shown is the sum of the contribution of CO_2 and BC.

Table 6.1 shows the radiative forcing contribution taking into account 134 releases per year, also showing the contribution at 5 and 10 years respectively, which do exceed the amount of RF given in the aviation reported in [8]. Table 6.2 shows the most predominant emissions of each type of propellant in the first scenario (134 launches per year), and also analyzes how these emissions would be in 5 and 10 years. On the one hand, it is worth noting that in the case of 10 years with this scenario, the 122 million metric tons emitted by the aviation industry annually will still not be exceeded.

	Emissions (kton)			***Total 5 years***			***Total 10 years***		
Propellant	CO_2	***BC***	NO_x	CO_2	***BC***	NO_x	CO_2	***BC***	NO_x
RP1$/LO_X$	45.77	1.06	-	228.9	5.3	-	457.7	10.6	-
Hybrids	0.234	47.42	0.519	1.11	237.1	2.6	2.23	474.2	5192.5
LCH_4/LO_X	92.8	0.0148	-	463.58	0.074	-	927.14	0.149	-

Table 6.2: CO_2,NO_x and BC emissions taking into account and scenario of 134 launches per year.(kilotons)

6.2 2 Launch Scenario (400 l/y)

The second scenario that will be evaluated will be considering 400 launches per year. This scenario is considered because several references mention that at some point it may be reached [49], for example, Virgin Galactic has announced plans to offer 400 flights each year [55]. The emissions shown in Tables 6.3 and 6.4 will be presented directly along with their analysis.

Propellant	**RF Contribution** $(mW/\mathbf{m}^2)^a$	***Total 5 years***	***Total 10 years***
RP1/LO_X	128.0024	640	1280
Hybrids	40.000012	200	400
LCH_4/LO_X	-		

Table 6.3: Radiative forcing contribution taking into account a 400 vehicle launches scenario.[a] value shown is the sum of the contribution of CO_2 and BC.

	Emissions (kton)			***Total 5 years***			***Total 10 years***		
Propellant	CO_2	***BC***	NO_x	CO_2	***BC***	NO_x	CO_2	***BC***	NO_x
RP1/LO_X	136.6	3.16	-	683.2	15.83	-	1360	31.66	-
Hybrids	0.668	141.55	1.5	3.3	707.77	7.7	6.69	1410	15.5
LCH_4/LO_X	276.77	5.92	-	1380	29.6	-	2760	59.2	-

Table 6.4: CO_2,NO_x and BC emissions taking into account and scenario of 400 launches per year. (kilotons)

Comparing these results with emissions produced in aviation, the emissions generated by kerosene and methane as fuels exceed those produced by the aviation industry, since to reach the levels achieved in a year by a launch vehicle using RP1/LO_x, approximately 500 LAX-LHR (Los Angeles-London) roundtrip flights with an occupancy of 300 passengers would have to be carried out. The emissions generated by hybrid propellant engines are, however, still acceptable and below those generated by the aviation industry, and propellants emitting NO_x products are acceptable compared to this industry since the global annual emissions reported by [24] were 2780000 tons.

6.3 3 Launch Scenario (1000 l/y)

Estimates for a scenario with 1000 launches per year are shown in tables 6.5 and 6.6, and an analysis is made based on available literature.

Propellant	**RF Contribution** $(mW/\mathbf{m}^2)^a$	***Total 5 years***	***Total 10 years***
RP1/LO_X	320.006	1600	3200
Hybrids	100.00003	500	100x10^3
LCH_4/LO_X	-		

Table 6.5: Radiative forcing contribution taking into account a 1000 vehicle launches scenario.[a] value shown is the sum of the contribution of CO_2 and BC.

	Emissions (kton)			***Total 5 years***			***Total 10 years***		
Propellant	CO_2	$\boldsymbol{BC}$	NO_x	CO_2	$\boldsymbol{BC}$	NO_x	CO_2	$\boldsymbol{BC}$	NO_x
$\boldsymbol{RP1/LO_X}$	341.6	7.9	-	1700	39.6	-	3400	79.1	-
Hybrids	1.67	353.9	3.9	8.3	1770	19.4	16.7	3500	38.7
LCH_4/LO_X	691.9	14.8	-	3400	74	-	6900	148	-

Table 6.6: CO_2,NO_x and BC emissions taking into account and scenario of 1000 launches per year. (kilotons)

Different references allude to a scenario of 1000 launches per year. For example, [52] states that radiative forcing caused by BC emissions by increasing the number of launches from present levels, around 100 per year to 1000 per year could lead to a similar radiative forcing as present-day aviation activities and could induce a regional radiative forcing of up to 0.1 W/m^2. This is evidenced in the table 6.5 since the RF values of RP1/LO_x have exceeded 0.1W/m^2 while the RF caused by hybrid engines has reached this point.
Likewise, [46] states that as a result of 1000 suborbital rocket launches per year, a persistent layer of black carbon particles would form in the northern stratosphere resulting from emissions from these rocket launches. These particles could have a significant impact on global atmospheric circulation and temperature distributions; it is inferred from this that particles from orbital flights in a scenario of 1000 launches per year would be more detrimental to this phenomenon.

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Chapter 7

Conclusions

An approximate study of the environmental impact generated by the different products emitted by the main types of propellants currently used in the space industry was carried out. This study took into account different future scenarios and their projections for five and ten years, respectively. Emissions in the stratospheric zone were considered because it is the most impacted zone due to its ozone layer, among other components.
Estimates of radiative forcing (RF) caused by CO_2 and black carbon emissions produced by different propellants were studied, where the contribution of kerosene and hybrid propellants stands out, concluding that in a scenario of 400 to 1000 launches per year, the RF value given by aircraft emissions is reached. On the other hand, it is worth mentioning that according to Virgin Galactic's estimate of reaching a launch rate of 400 launches per year, the RF generator would still be acceptable, and on the other hand, the predominant emission would be BC with a value of 141552 tons per year, which is below those emitted by industrial aeronautics.

• As for the emissions from solid rocket motors, these are dominated by CO_2, chlorine, and alumina, products that are capable of depleting the ozone layer. However, how alumina affects the environment is still uncertain, so if the use of this type of propellant continues to be used, these emissions and how they impact the atmosphere must be studied in detail.
• With this analysis, we can conclude that the CO_2 emissions from rockets with current launch rates, as well as in a scenario of 1000 rocket launches, have a smaller impact on the environment than the aviation industry. As a consequence, talking about carbon dioxide emissions should not be included in any discussion of space transport's climate impact. It also follows that cryogenic propellants are the cleanest, specifically hydrogen-fuelled rockets as they only emit water vapor which has the lowest contribution to environmental impact according to the references.
• It is very necessary to start establishing ways to regulate emissions from space vehi-

cles. This is because a future of increasing activity is expected. Underestimating current emissions can lead to problems such as those caused by space debris, which at first were considered insignificant, and nowadays alternatives are being sought to solve this issue. It is possible to analyze a scenario in which the number of launches or even the type of propellant used for launches may need to be regulated or controlled. This is due to the potential for ozone depletion. If this scenario becomes a reality, then we will have to quantify exactly how many launches, and the impact of launches on the environment.

Other types of alternatives are also emerging such as changing propellants including liquid methane, water-powered rockets (EcoRockets), launch companies have chosen to sustainable propellants, biofuel (bio-propane) and waste plastic-derived artificial kerosene, 'Ecosene', respectively.

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Appendix A

EMISSIONS GENERATED FOR LAUNCH VEHICLE

This appendix shows different emissions that are generated by some launch vehicles throughout history, together with their propellant type respectively, in table A.1 The values have mass dimensions (in tons) of Greenhouse Gases and Particulates Generated in Launch Vehicles. Carbon dioxide is the total amount for the launch. Water vapor is determined for the stratosphere and above since water vapor released in the troposphere is short-lived. Data adapted from [17].
At the table A.1, SLS: Solid Rocket Motors, N_2O_4/UDMH: Dimetilhidrazina (liquid propellant). On the other hand, Table A.2 shows the alumina and clhorine emissions deposited above 15 km from different rockets .

Vehicle	**Total CO2**	**Soot**	**Stratos. H2O**	**Stratos. NOx**	**Propellant Type**
Brazil					
VLS	7.2	0.22	5.25	0.01	SRM
China					
Kaitouzhe-1	11.9	0.19	3.55	0.00	SRM
LongMarch2D	101.2	0.43	49.08	1.05	N2O4/UDMH
LongMarch2F	198.7	1.05	105.50	2.21	N2O4/UDMH
LongMarch3A	93.6	0.41	74.05	1.0	N2O4/UDMH
LongMarch3C	173.4	0.68	109.19	1.75	N2O4/UDMH
LongMarch4B	107.9	0.60	61.81	1.20	N2O4/UDMH
LongMarch5	359.3	1.89	94.04	0.00	RP-1/LOX
Russian					
DNEPR-1	74.7	0.36	36.64	0.79	N2O4/UDMH
SoyuzFG	242.9	1.27	63.70	0.00	RP1-LOX
SoyuzU/Ikar	243.3	1.27	64.01	0.01	RP1-LOX
Vostok	179.3	1.24	45.09	0.15	RP1-LOX
Europe					
Ariane1	105.7	0.80	84.94	1.42	LH2/LOX
Ariane44P	121.2	0.80	84.94	1.42	LH2/LOX
Ariane5	170.5	3.16	299.14	1.99	LH2/LOX
VEGA	7.5	0.05	4.39	0.89	SRM
India					
ASLV	11.3	0.02	0.68	0.00	SRM
PSLV	97.4	1.90	53.68	0.44	SRM
GSLV	127.8	1.27	85.90	0.31	SRM
USA					
Athena I	19.3	0.24	6.18	0.01	SRM
Atlas IIAS	156.4	1.63	82.08	0.01	SRM
Atlas IIIB	151.3	0.87	68.56	0.00	RP1/LOX
Atlas V X1Z	245.9	1.92	105.84	0.01	RP1/LOX
Delta 4M (5,4)	36.1	1.41	221.37	0.01	LH2/LOX
Falcon 9	326.6	1.94	94.72	0.00	RP1-LOX
Falcon Heavy	976	7.79	301.77	0.02	RP1-LOX
Space Shuttle	442.9	4.27	975.70	0.22	SRM-LH2/LOX
Titan IVA 401	159.5	2.38	117.71	0.60	
Blue Origin PM-2	17.4	0.3	16.0	0.001	SRM
SLS	538	6	1346	0.3	SRM

Table A.1: Different emissions generated by various rockets with their respective propellant type. Adaptem from [17]

Vehicle	**Chlorine (tons/launch)**	**Alumina (tons/launch)**
Titan IVB SRMU	56.9	87.8
Titan IVA SRMU	36.9	69.0
Delta II 79X5H	10.4	16.1
Delta II 73X5	0.4	0.7
Delta II 69X5	6.0	10.0
Delta II 59X0	6.1	9.4
Delta IV H	0.0	0.0
Atlas V X3Z	8.8	14.3
Pegasus	3.2	4.4
Space Shuttle	92.2	129
Space Launch System	130	182
Athena 1	5.8	8.7
Minotaur 1	3	4.5
Minotaur V	11.0	16.9
Ariane 4LP	0	0
Ariane 5	55	84.9
N2	0	0
H2 2024	22.5	31.3
M-3SII	4.3	6.0
PSLV	20.1	27.6
KSLV1	0.976	1.339

Table A.2: Chlorine and alumina emissions from different launch vehicles. Adapted from [17]