LIFE CYCLE ASSESSMENT OF ALTERNATIVE LAUNCH METHODS

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Abstract

The ever-increasing privatization of the space sector and rise of commercial space travel raises the need to consider the environmental impact of space flight, similarly to aviation. To assess the impact of space launch systems, it is necessary to use life cycle assessment (LCA) methods to produce information across all phases of the life cycle. This approach, extensively used in industry, allows for the identification of high impact processes and materials that may not be initially considered. This study applied LCA to two different launch methods but with similar missions.

Key Words: New Shepard, SpaceShipTwo, Environmental Impact, Life Cycle Assessment, Launch Method

1. Problem Statement

This project aims to develop a life cycle assessment technique that can be used to effectively model the environmental impact of various launch systems with a case study on the launch methods utilized by Blue Origin's New Shepard (Fig. 1) and Virgin Galactic's SpaceShipTwo (Fig. 2). These two systems have been selected as they are both suborbital missions with the primary goal of providing a space tourism experience. Because of largely different launch methods and fuel types, one cannot decisively say which vehicle has the lowest environmental impact when a cradle to grave life cycle assessment is performed.

Figure 1 - Blue Origin's New Shepard [2]

Figure 2 - Virgin Galactic's SpaceShipTwo [1]

1.1. Problem background

Currently, the world produces over 40 billion Tons of CO_2 per year [4]. The majority of human-made CO_2 is produced due to the combustion of fossil fuels. In the United States, the burning of fossil fuels for electricity production, transportation and industrial uses accounts for approximately 77% of the nation's CO_2 production (Environmental Protection Agency, 2019). A significant portion of emissions comes from transportation and the quantity of road vehicles. In the US, the average passenger vehicle is estimated to produce a relatively insignificant 4.6 Tons of CO_2 per year [5], however considering the quantity of motor vehicles globally, the total impact is not insignificant. Currently, space travel and the practice of launching payloads into orbit contributes a negligible amount to our global emissions with launches estimated to produce about 1,000 kg CO_2 eq depending on the propellant. In 2021 there were 146 spacecraft launches worldwide, an increase of 30 launches over the previous year and the most space launches in one year in world history. Companies like Virgin Galactic expect to facilitate 400 launches per year, per space port [6]. As the number of space flights increases, a once insignificant contribution to global emissions will become substantial. Therefore, it is important to explore how alternative launch systems affect the environmental footprint.

In recent years, various private space agencies including Blue Origin, SpaceX and Virgin Galactic have explored reusable launch options with key parts of the rocket designed to be recovered after launch [7]. Virgin Galactic's SpaceShipTwo is carried between a twin cabin aircraft (WhiteKnightTwo) up to approximately 15,000 m where SpaceShipTwo is released, from here it flies into the exosphere and glides back [8]. In comparison, Blue Origin's New Shepard launches like a standard spacecraft and all parts of the launch vehicle are recovered and reused for multiple launches.

1.2 Research and objectives

At present there is minimal research into the environmental impact across product life cycles in the space industry. With the rise of space tourism, and the increasing volume of space traffic that will come with it, it is important to consider how environmental impact can be assessed. The primary goal of this project is the development of a methodology to assess the environmental impact of launch vehicle systems using LCA.

LCA is a process for assessing environmental impact across a product's life cycle, using a method defined by the International Standards Organization (ISO). LCA looks beyond basic level conceptions regarding emissions from a life cycle perspective, from cradle to grave, by viewing the product at a systems level. This technique will be demonstrated via a case study with focus on two launch methods: Virgin Galactic's SpaceShipTwo and Blue Origins New Shepard.

2. Background and literature review

Historically payloads launched into orbit were primarily for military and scientific purposes. In recent years however, the number of commercial payloads has increased due a growing private sector [9]. One such industry is space tourism. Pioneering the use of reusable rockets to minimize cost, space travel is expected to become more affordable for individuals. To successfully monetize their business, we expect to see huge increases in the volume of launches per year. As the sector becomes more significant we can expect more substantial environmental impacts, throughout the product life cycle [10].

During launch, emissions from the engines are of primary concern. The extent of pollution depends on the type of fuel used, with effects varying by altitude. Currently, there are four types of propellants: solid, liquid and hypergolic. The propellants assessed in the report are solid propellant (Hydroxyl Terminated Polybutadiene) and liquid propellant (Hydrolox & Kerosene). Solid propellants, which mainly contains solid aluminium fuel and ammonium perchlorate, emit HCl and Al_3O_2, directly resulting in ozone loss. Although, a solid propellant is mostly used in the lift-off stage and only effects the lower stratosphere, significant ozone depletion occurs and could affect ozone depletion globally. Hydrogen based liquid propellant, which contains liquid oxygen and liquid hydrogen, generally emits H_2, OH, H_2O and NO_x. The effect of liquid propellant on ozone depletion is substantially less in comparison to solid propellant. Water vapour produced by some liquid propellants can create a mesospheric cloud that can cause radiative forcing [11].

A study on black carbon emissions, i.e. soot, from 1,000 suborbital rockets launches per year shows that black carbon emissions at this launch volume could be comparable to current subsonic flight. The current black carbon layer in the northern stratosphere can directly affect the global ozone circulation and temperatures due to the Brewer-Dobson (BD) circulation with significant impact on the ozone layer, directly affecting the temperature and leading to a decrease in the amount of sea ice in the polar zones [12]. Therefore, the Global Warming Potential (GWP) of the black carbon is expected to be high, with the GWP of 680 kg of CO_2, for 100 years after emissions, and 2200 kg of CO_2, for 20 year of emissions [13].

Although outside the scope of this assessment, it is important to consider the local effects of launch systems on local flora, fauna, and human life. A study on insect populations, conducted around the South China Satellite launch centre Wenchang, found that rocket launches had a negative impact on the biodiversity near launch sites, including a decrease in general insect populations [14]. Contamination due to manufacturing processes can also have a negative impact on human health. Contaminants such as perchlorate, a component of some rocket fuels, have been found in drinking water [14].

While alternative launch solutions present the opportunity for radical changes to the launch process and potentially to environmental impact, there are alternative routes by which impacts can be managed and launches optimized. As with terrestrial and non-terrestrial vehicles, it is suggested that the process of "light-weighting" results in a reduction of the environmental impact of spacecraft for a range of fuels including Liquid Nitrogen Tetroxide-Unsymmetrical Dimethylhydrazine and Oxygen-Rocket Propellant rockets [15]. The process of light-weighting has origins in the automotive industry but has been adapted to suit aerospace design. It involves the reduction of weight through the substitution of a material for an equivalent or higher performing material of a lower mass, thus reducing overall mass while not compromising performance [4]. This could lead one to assume that the mass of the craft plays a decisive role in the overall emissions throughout the product life cycle, with reduced emissions in both manufacturing and fuel expenditure. If we only consider the surface level impact and ramifications of particular design decisions, it is possible to misidentify areas of high environmental impact. In a system as complex as a spacecraft, it is more than likely key emission producing aspects will be overlooked. Therefore, it is important to utilise life cycle assessment to identify non-obvious high impact processes.

A particular area in which assumptions may be incorrectly drawn is with respect to fuel emissions. Virgin Galactic uses kerosene-based fuel in WhiteKnightTwo and HTPB in SpaceShipTwo, whereas Blue Origin utilize a traditional Hydrolox fuel in New Shepard. At a basic level we may assume that the kerosene and HTPB fuels are substantially more impactful than the hydrolox fuel as the by-product of hydrolox combustion is water, largely considered insignificant with respect to global emissions. However, considering the production processes for hydrogen and oxygen, the constituents of hydrolox fuel, the answer is less obvious.

Blue Origins New Shepard Rocket uses the Blue Engine 3 (BE-3) rocket engine [16], a liquid hydrogen-liquid oxygen engine (LH_2/LO_x or Hydrolox) developed in-house that utilizes a cryogenic tap-off combustion cycle in order to produce thrust [17]. In this system the hydrogen serves as the fuel while the oxygen serves as the oxidiser. Both components of the fuel are gaseous at room temperature and as such have extremely low densities, thus making it counterintuitive to store them in gaseous form from a weight savings perspective. Both the fuel and oxidisers are stored in their liquid, requiring the LO_x to be stored between -183 and – 219 degrees Celsius and the LH_2 to be stored between -253 and -259 degrees Celsius.

In the BE-3 rocket engine the major inputs are hydrogen and oxygen, with the output being water in the form of water vapor, in addition to any non-combusted hydrogen due to the fuel rich nature of the mixture. Hydrogen can be produced via several methods, however there are three methods that are predominantly used. Steam methane reforming involves the production of hydrogen through the reaction between some biogas, usually methane and steam. This is the most commercially viable option when large flow volumes are required. This method can produce around 70-75% hydrogen, with the remaining 25-30% by-products being greenhouse gases [18]. Although the most common method by which hydrogen is produced, it is estimated that the emission by-products are equivalent to that of the biofuel being burned directly. Another method requiring hydrocarbons is gasification, where hydrocarbons react with oxygen at a non-ideal stoichiometric ratio. This leads to the production of carbon monoxide and hydrogen through a choked combustion reaction. A with steam methane reforming, the greenhouse gas by-products are not ideal for limitations to climate impacts. Electrolysis of water is a process that involves the separation of water molecules into their constituents, hydrogen and oxygen. Although producing extremely pure hydrogen, with little to no emissions by-products, the energy requirements are high, requiring between 2-2000kW per electrolyser [18]. In terms of sustainability in the minimizing of emissions, electrolysis is the most promising. Due to the high energy requirements, it is important to consider where the power comes from when categorizing hydrogen produced through electrolysis as a “clean” fuel. Furthermore, electrolysis remains the most cost and energy expensive method, and as such is not considered viable in situations where large flow volumes are required.

Similarly, there are a number of methods by which oxygen is produced, with vary energy consumptions and greenhouse gas emissions, these include: Cryogenic Distillation, pressure swing absorption and ion transport membrane [19]. Cryogenic distillation involves the distillation of air at extremely low temperatures, with different gases filtering out based on their boiling temperatures. This method is advantageous in the production of oxygen as an oxidizer for rocket fuels as the finished product is already present in liquid form. Despite the high energy requirements for cooling to such extremely temperatures, this is the most cost effective and energy efficient method for acquisition. Pressure swing absorption involves forcing air through synthetic membranes at high pressure. Nitrogen and other gases are filtered out through absorption by the synthetic materials or via carbon molecular sieve. This method generally produces less pure oxygen than via the cryogenic distillation. The final, and least common method is via ion transport membrane, ionized oxygen particles in air a forced through a membrane, where the now pure oxygen particles reform on the other side. This method has high energy requirements due to the high temperatures required for the ionization of oxygen.

Water vapor, the by-product of hydrolox rockets, plays a key role in the earth’s greenhouse effect, trapping a significant portion of the heat the earth receives from the sun. This heat is necessary to keep the planet warm and maintain life. As the atmosphere warms due to standard greenhouse gas emissions, excess heat is trapped in the atmosphere, which in turn leads to the formation of more water vapor, exacerbating the effects of increased CO_2 eq. emissions in the atmosphere. Some studies suggest that an increase of 1-3% per degree of surface warming in atmospheric water vapor as result of increased emissions [20]. Increasing atmospheric temperatures can also contribute to a greater lifetime of water vapor in the atmosphere, suggesting a longer hydrological cycle, i.e. a greater number of droughts and water related extreme weather events. However, this is due to higher atmospheric temperatures, and not the result of increased levels of atmospheric water vapor brought on by warming [20] .

Although water vapor plays a substantial role in the planetary greenhouse effect, it is hard to equate increased levels of water vapor emissions, to any significant changes to the global climate. However, as with other emissions, the presence of greenhouse gases is often worse than those emitted at surface level. There is little available research as to how water vapor can impact the environment when emitted in the upper atmosphere. It is important to note that unlike fossil fuels, hydrogen is not readily available in the environment and must be produced, as such hydrogen is a secondary fuel and effectively functions as a battery. The sustainable nature of the hydrogen is relative to the methods by which it was produced, with steam methane reforming being the least environmentally friendly and electrolysis of water being the most, although this depends primarily on the sources for the energy required.

As previously mentioned, the factor that will be used to evaluate emissions impacts in the life cycle analysis comparison is the global warming potential (GWP). This is the amount of the carbon dioxide emissions equivalent to that specific gas. Black carbon has a GWP 100 of 1,112 kg of CO_2, This mean that 1 kg of black carbon will be equivalent to 1,112 kg of CO_2 over the course of 100 years. [21]

3. Methodology and engineering design

The research methodology will outline the general overview of how the data will be gathered and analysed. Furthermore, an in-depth description of the LCA process will be discussed, any adjustments made to the methodology will be accounted for. This project will not conduct any new research, instead life cycle assessment inventories will be constructed with available information for both projects (Blue Origin/Virgin Galactic). Where information is unavailable, estimates will be used, with subsequent uncertainty and sensitivity calculations used to strengthen the data.

3.1 Life cycle assessment methodology

Life cycle assessment is an established method for assessing the environmental impacts of various product systems, in addition to providing comparison between similar products. This report intends to follow life cycle assessment industry standard *ISO14040*. This method breaks the LCA into four sections are: goal definition, scope definition, inventory analysis/assessment and impact assessment [22]. In some instances, goal definition and scope definition are combined. Figure 3 depicts the framework for LCA based on *ISO14040*.

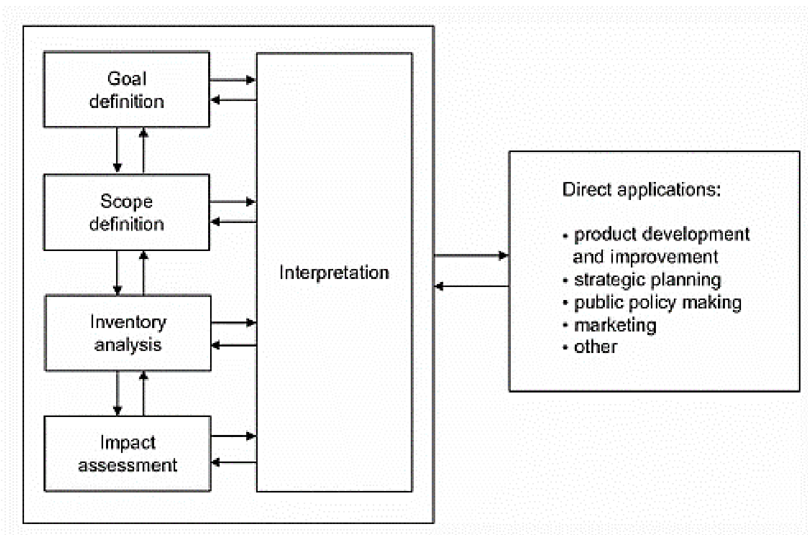

Figure 3 - Modified LCA Framework based on ISO14040 [22].

The definition of the goal and scope of the project is essential to LCA for several reasons. The goal outlines the purpose of the LCA, answer the question as to why the LCA is being conducted. Furthermore, the stakeholders for the project should be outlined. This often shapes how data is presented, is the target audience the public or is the paper being commissioned for commercial use.

The scope is an integral part of the LCA and involves the definition of the function of the product, the functional unit and reference flows, product system and system boundaries. The function is what defines the intended purpose for the product(s). The functional unit is what quantifies the function of the product as defined by the administer of the LCA. The functional unit is very important, as the results of the LCA can be heavily swayed depending on how the functional unit is defined. In addition, similar functional units can allow for comparisons to be drawn between LCA's. The reference flows are created to identify how much material is required to produce one functional unit worth of product, this ties into the inventory analysis for the product. Finally, the system boundaries need to be set, often reference flows and inventories can be incredibly complicated, especially with respect to projects with a significant number of parts. Typically, system boundaries are defined such that any material/process that contributes less than some value of mass/energy to the overall system is excluded from the system. Any materials/processes that have minimal mass or energy contributions, but high impact are included in the product system. The product system is essentially the model designed to account for the overall product life cycle, once the actual product has been defined, the downstream (materials acquisition, product, transport etc.) and upstream processes (end of life: landfill, recycling, composting etc.) can be defined [23)].

Inventory analysis or LCIA (Life Cycle Inventory Assessment) is the next stage in performing LCA, forming the backbone of the numerical data produced during the LCA. This stage in the process involves research and the quantifying of mass and energy inputs for various upstream and downstream processes. It is important to identify what materials compose the product system, usually by mass, and identify the input and output processes, materials, and by-products. With those processes being linked to their own input and output processes etc. The resulting system could be described as a “Tree” with the full product system at the top, cascading into the various products and product that comprise the product system. This part of the LCA is often exceedingly complicated and requires software to produce accurate models.

Due to the sheer complexity and volume of processes required to compile one life cycle inventory, life cycle databases can be used. These databases are comprised of various materials and processes, with inputs and outputs already identified and linked for easy of use. A popular software for conducting LCA is OpenLCA, with life cycle inventory databases available to download. These databases are typically constructed by other people conducting life cycle assessment and added to over time. One of the more common databases used is EcoInvent (X), with X denoting whichever iteration the databases is currently up to. Data for the LCIA can be gathered by several means. Material data for products can be acquired via records, schematics, and bills of materials with additional data attained from literature [22)]. For process data, it is important to gather data from the site of major processes, this maximizes accuracy and ensures that generic data is not included in place of data specific to a product system [23)].

Impact assessment is the final step in the LCA process, this involves the calculation of emissions and environmental impacts based on the inputs and outputs of the product system calculated in the LCIA. It is often too complicated or expensive to address all environmental impacts, as such several specified impact categories are selected. Depending on the project these can include climate impacts, fossil depletion, acidification, eco-toxicity, human-toxicity, and eutrophication to name a few. As the most pressing matters, and the issues that most individuals are conscious of, is climate change and fossil depletion, you will see these in a vast majority of contemporary life cycle assessments. This is one key section where data for the LCA can be affected by stakeholders or the requestees of the LCA. In analyzing a product system, but choosing not to investigate climate impacts, one could conclude that a product is relatively eco-friendly, yet the LCA does not tell the full story. As such is important to choose a range of relevant impact categories in addition to specifying which impact categories have been excluded and why, for the benefit of the reader.

3.2 Study specific methodology and challenges

In line with the primary research questions, this project aims to produce an LCA model able assess the environmental impact of rocket launches, with a case study of Virgin Galactic and Blue Origins rockets. Data will be gathered based on pre-existing research, information available from the subjects of the case study and life cycle assessment databases for primary emissions data during manufacturing. The first two parts, goal and scope definition, have already been completed, however are not included in this paper. The life cycle inventory, typically the most time intensive aspect of the LCA is underway, with no results finalized yet. The final step, the impact assessment, can only be conducted accurately once a complete life cycle inventory is available.

The life cycle inventory will prove to be the most challenging aspect of the LCA. A lack of available data is expected to present a significant challenge. Given the complexity of the product system in questions, producing an accurate model is difficult. However, there are several tools and techniques available to simplify the processes without forsaking accuracy. Firstly, life cycle assessment software, such as

OpenLCA, has inbuilt databases and databases available for download that have been compiled by LCA practitioners to simplify the data gathering stage of LCA. Additionally, the cut-off criteria described in the scope definition provide a means to simplify the product systems without adversely affecting accuracy. Given the mass of both craft is more than 30,000 kg, negligible parts by mass can be discounted, typically those less than 1% of the overall mass. Finally, given the complexity of the system and the limited data available, we can focus on the aspects of the craft that have the highest impacts. Typically, with any transportation based LCA, the impacts during the use life cycle phase far exceed those of the manufacturing stages. We can loosely approximate a product system and then generate an impact assessment based on the approximation. From here areas of high impact can be identified and focused on. As stated, transport LCA often have high impacts due to the combustion of fuel, as such this would become an area of high focus.

Section three is expected to occupy a significant portion of the available time frame to work on this project due to the sheer complexity of the product system in question. In addition, a lack of available data and previous works to draw off will add to the challenge. Furthermore, the choice as to how to incorporate the vary life cycles lengths and maintenance frequency, relative to the functional unit, for the end-of-life processes needs to be accounted for in order to present a fair comparison. Typically, during LCA significant processes inputs and outputs are recorded over the course of, at maximum, one year at the site of manufacture or treatment. As this is not possible for this project, some estimates, in addition to data available from literature will be used.

We intend to use the pre-existing EcoInvent 3.8 and Strathclyde Space Systems database (SSSD) in OpenLCA to build the life cycle inventory. However, we are aware that there is a high likelihood that data for the use life cycle stage will likely not be available in the EcoInvent database as it relies on data from previously conducted LCA. Any data unavailable in EcoInvent 3.8 were researched and computed separately and input into OpenLCA. As both craft are technically “reusable” this must be incorporated into the life cycle assessment, yet we know that both craft do not share the same mission length, nor are engines and other major parts interchanged at the same intervals. This can be achieved by calculating the manufacturing cost of the entire life cycle, including replacement parts, and taking the average per launch. This means that parts require more infrequent replacement and have a greater life span should produce lesser impacts.

One important consideration is the launch infrastructure. This hardware plays an important role in every launch, and the impact of construction needs to be calculated in order to determine whether they are negligible or not. This is important as, in the case of New Shepard, the launch infrastructure is purpose built, whereas Blue Origin can launch from pre-existing airfields with some adjustments. This may only be possible if sufficient data is available.

4. Life Cycle Inventory Analysis Overview

Relevant mass and energy inputs for the product system have been compiled into a life cycle inventory using the open-source life cycle assessment software OpenLCA. Foreground data has been compiled based on literature and available information regarding both systems. Background data has been taken from the Strathclyde Space Systems Database (SSSD) [24)] and Ecoinvent 3.8 life cycle inventory database. Where specified materials or processes are unavailable in databases, new processes have been created accordingly or suitable approximations have been given.

Given this report is a comparison between two space systems with equivalent missions and similar development times, this life cycle assessment will only include aerospace phase E1, focusing on launcher related activities. Phases A – D, which include research, development and testing are expected to be largely equivalent between both systems and as such are not included.

4.1 New Shepard Booster and Capsule

Blue Origins New Shepard Rocket uses the Blue Engine 3 (BE-3) rocket engine [16], a liquid hydrogen-liquid oxygen engine (LH_2/LO_x or Hydrolox) developed in house that utilizes a cryogenic tap-off combustion cycle in order to produce thrust [17]. In this system the hydrogen serves as the fuel while the oxygen serves as the oxidiser. Both components of the fuel are gaseous at room temperature and as such have extremely low densities, thus making it counterintuitive to store them in gaseous form from a weight savings perspective. As such both the fuel and oxidisers are stored in their liquid, requiring the LO_x to be stored between -183 and – 219 degrees Celsius and the LH_2 to be stored between -253 and -259 degrees Celsius. Given the private nature of Blue Origin, materials specifications and quantities are hard to come by. The model for New Shepard has been constructed according to data available in literature and the SSSD for similar cryogenic rockets. It is worth noting that all other rockets are orbital, while New Shepard is sub-orbital. Furthermore, the model assumes a largely aluminium and aluminium metal matrix composite, however, it is equally likely that, similar to SpaceShipTwo, New Shepard utilizes carbon composite materials in higher volumes than estimated in this model.

Table 1 - Estimated emission from SpaceShipTwo, adapted from FAA[25]

Description	CO_2	CO	H_2O	VOC	NO_x	N_2	H_2
Emissions per launch							
Using Nylon/N_2O	2,717	730.12	2,820	0.00	61.23	8,695	339.09
Using HTPB/N_2O	3,679	1,516.25	1,532	0.00	61.23	8,543	21.38
Annual Emissions (30 launches)							
Using Nylon/N_2O	81,505	21,904	84,590	0.00	1,837	260,859	10,173
Using HTPB/N_2O	110,374	45,488	45,946	0.00	1,837	256,276	642

a. Note: CO_2 = carbon dioxide; CO = carbon monoxide; H_2O = water; VOC = volatile organic compound; NO_X = nitrogen oxides; N_2 = nitrogen; H_2 = hydrogen; N_2O = nitrous oxide

Two alternative models are presented for the New Shepard reusable booster, one featuring the aluminium matrix composite design, another that replaces the aluminium matrix composite parts of the design with carbon fibre reinforced plastics.

4.2 LH_2/LOx Manufacturing and Launch

New Shepard uses a cryogenic fuel combination of liquid oxygen and hydrogen. The fuel mass for New Shepard was estimated based on the assumed overall mass of the craft (approx. 36 tonnes) and the expected I_{sp} for the launcher. I_{sp} for New Shepard is expected to be approximately 350s. Given the following, we can calculate expected mass flow rate:

$$Isp = \frac{F}{\dot{m}g_0} \tag{1}$$

$$350 = \frac{490{,}000}{\dot{m}\,9.8}, \dot{m} \ = 161.29\ kgs^{-1} \tag{2}$$

New Shepard fires for 141 seconds, giving a fuel mass of 20, 142 kg. The balanced stoichiometric reaction that occurs between LH_2 and LO_x to produce thrust is as follows [26]:

$$2H_2 + O_2 \Rrightarrow 2H_2O \tag{3}$$

Although the stoichiometric molar ratio is 2:1 hydrogen to oxygen, the mass ratio is closer to 1:8 due to oxygens substantially higher molar mass, see below:

$$Hydrogen\ atomic\ Mass: 1.0078\ g/mol$$

$$Oxygen\ Atomic\ Mass: 15.899\ g/mol$$

$$One\ Mol\ H_2\ mass: 2.0156g, One\ Mol\ O_2\ mass: 31.798g$$

$$H_2 : O_2\ molar\ ratio\ 2:1, mass\ ratio: \frac{31.798g}{2.0156g\ \times 2} = 7.88 \quad (4)$$

Despite the ideal oxidizer to fuel mass ratio being 8:1, it is not feasible for most LH_2/LO_x rockets to use this ratio. LH_2/LO_x are typically run rich to minimize temperatures in the combustion chamber, improve the specific impulse of the engine and increase the nozzle efficiency due to the presence of non-combusted hydrogen particles. As such most Hydrolox engines tend to run an oxidizer to fuel ration of 5:1 – 7:1 instead of the ideal 8:1 ratio. Due to the private nature of Blue Origin's business, the specific ratio for the BE-3 engine is unknown, but we can assume that it lies somewhere in this margin. As such the O/F ratio specified in the SSSD has been used. Manufacturing and production inputs and outputs for LOx/LH_2 fuel have been used in the model in addition to expected emissions from launch. Expected emissions for 1kg of hydrolox fuel are shown in Figure . As expected, most of the output is water vapour.

4.3 WhiteKnightTwo and SpaceShipTwo

While traditional rockets launch from sea level, Virgin Galactic has become a pioneer in non-traditional launch methods for spacecraft, with SpaceShipTwo launched from the mothership WhiteKnightTwo. WhiteKnightTwo carries SpaceShipTwo to an altitude of 15 km, taking approximately 45 min. SpaceShipTwo then detaches from the carrier and ignites RocketMotorTwo, firing for roughly 70 seconds. After engine shut down, the vehicle will steadily climb to 100 km. SpaceShipTwo utilizes a unique feathering system prior to and during re-entry before gliding back and touching down on the runway at Space Port America [27].

Outputs

Flow	Amount	Unit
Al2O3 emissions, from launch	0.00000	kg
Black carbon, from launch	0.00000	kg
Carbon dioxide, from launch	0.00000	kg
Carbon monoxide, from launch	0.00000	kg
Chlorine oxide radicals, from launch	0.01600	kg
Hydrogen chloride, from launch	0.00000	kg
Hydrogen oxide radicals, from laun...	0.00300	kg
Hydrogen, from launch	0.24800	kg
Launch Event by Propellant Type ...	**1.00000**	**kg**
Methane, from launch	0.00000	kg
Nitrogen oxide radicals, from launch	0.00100	kg
Nitrogen, from launch	0.00000	kg
Water vapour, from launch	0.99200	kg

Figure 4 - Launch Emissions LH_2/LOx

While specific material composition data for both SpaceShipTwo and WhiteKnightTwo are largely unavailable, estimates can be made based on literature and other sources. Both SpaceShipTwo and WhiteKnightTwo are scaled up, approximately twice the size, versions of their predecessors SpaceShipOne and WhiteKnightOne. SpaceShipOne is noted as featuring a Nomex – carbon fibre reinforced polymer sandwich panel fuselage. [28] SpaceShipTwo is stated to be all carbon composite. One of the only disposable parts of SpaceShipTwo is the engine, referred to as the Case Throat Nozzle (CTN), this part of the craft is required to be replaced after every launch. While exact data is not available, it is based on a similar motor used in SpaceShipOne, which was comprised of graphite, epoxy, phenolic resin, glass fiber and temperature resistant composite insulators, likely some variation of aramid fibers.[28] Based on this information we can create a basic model for SpaceShipTwo and the CTN. Assuming statements regarding SpaceShipTwo's material composition are truthful, the model has been designed to feature predominantly carbon fibre by mass.

Figures 5 and 6 display mass inputs required to produce 1 kg of the specified rocket. WhiteKnightTwo is also specified as being predominantly some form of carbon fiber composite, however, the engines used, in this case four Pratt and Whitney PW308A engines weighing approx. 622.3 kg each. The overall fuel tank mass is expected to be approximately 400 kg approx. In this model a composite tank was used. The weight of the fuel tank of WhiteKnightTwo is estimated from the fuel system weight equation, as shown in Eq. 5. [29]

P Inputs/Outputs: RocketMotorTwo (Case/Throat/Nozzle)

Inputs

Flow	Amount	Unit
aluminium alloy, metal matrix com...	0.20000	kg
aluminium removed by milling, av...	0.20000	kg
Carbon Fibre Reinforced Polymer	0.30000	kg
electricity, medium voltage, produ...	17.00000	kWh
epoxy resin insulator (SiO2), at plan...	0.10000	kg
glass fibre	0.12500	kg
graphite	0.07500	kg
phenolic resin	0.10000	kg
sheet rolling, aluminium	0.05000	kg
Titanium, TiAl6V4	0.10000	kg

Figure 5 - CTN inputs, From SSSD.

P Inputs/Outputs: SpaceShipTwo

Inputs

Flow	Amount	Unit
aluminium alloy, AlMg3	0.06110	kg
Carbon Fibre Reinforced Polymer	0.91930	kg
Propellant Tank	0.07350	kg
Propulsion Feed System	0.01838	kg
synthetic rubber, at plant - RER	0.02496	kg
Zerodur Glass	0.02756	kg

Figure 6 - SpaceShipTwo inputs, From SSSD.

$$W_{fuel\ system} = 36.3\left(N_{eng} + N_{ft} - 1\right) + 4.366 \cdot {N_{ft}}^{0.5} \cdot {V_{ft}}^{0.333} \qquad (5)$$

where, $W_{fuel\ system}$ is weight of the fuel system (kg), N_{eng} is number of engines, N_{ft} is number of fuel tanks, where the number of tanks must be greater than or equal to the number of engines, and V_{ft} is total fuel tank volume (litres).

Since WhiteKnightTwo uses Pratt & Whitney Canada PW300 engines and 3630 kg kerosene as fuel. It's assumed that the number of fuel tanks is the same as the number of engine and the total volume of fuel tank will be calculated from the density of the kerosene, which is 0.786 kg/litre.[30] Therefore, with the volume of fuel tank of 4,537 litres, the weight of WhiteKnightTwo fuel tank is 398.25 kg.

4.4 N_2O/HTPB Manufacturing and Launch

SpaceShipTwo uses a hybrid rocket fuel, hydroxyl-terminated polybutadiene (HTPB) with nitrous oxide as an oxidizer. SpaceShipTwo is expected to burn approximately 7028 kg of N_2O/HTPB fuel, using 867 kg of HTPB and 6161 kg of nitrous oxide at an approximate 7:1 oxidiser to fuel ratio. The expected manufacturing emissions inputs and outputs and relevant up and downstream processes are available for an N_2O/HTPB fuel mixture in the SSSD.

The expected launch event emissions for a hybrid fuel are unavailable in the SSSD database. While becoming more common, hybrid rocket engines are relatively rare, with most launchers using either a solid or liquid fuel as opposed to a combination of both. Launch emissions estimates specifically for SpaceShipTwo are available based on a environmental assessment study conducted on Virgin Galactic and SpaceShipTwo in 2012, Table 2 displays the expected emissions outputs per kg of propellant input, at the time SpaceShipTwo was also undergoing testing using a nylon-based fuel.

While useful in providing emissions estimates per launch, the emissions indices do not provide any relevant data on black carbon emissions per unit mass of propellant. Considering the GWP 100 potential of BC is more than 1,000 kg CO_2 eq. it is important to consider this in the launch emissions for hybrid rocket motors. In a 2010 study Ross suggests that a plausible value for BC launch emissions for hybrid rocket motors could be in the range of 60 grams BC per kg of propellant emitted.[12] While plausible, other literature suggests that the black carbon emissions depend largely on the oxidiser to fuel ratio. Figure 7 shows the relationship between O/F ration and the fraction of carbon in exhaust products.

Table 2. Emissions per unit mass of propellant. Adapted from FAA.[25]

Exhibit 4-3. Estimated Emission Indices for HTPB/N_2O and Nylon/N_2O Propellants (mass emitted/unit mass of propellant)[a,b]

Propellant	CO_2	CO	H_2O	VOC	NO_x	N_2	H_2
Nylon/N_2O	0.178	0.048	0.184	0.0	0.004	0.568	0.022
HTPB/N_2O	0.240	0.099	0.100	0.0	0.004	0.558	0.001

Figure 7 suggests that for N_2O fuels, any O/F ratio greater than 3:1 should produce a negligible concentration of black carbon in the exhaust, particularly for craft operating close to maximum ISP. [3] It is worth noting that due to the nature of hybrid rocket motor designs, the O/F ratio is not always consistent throughout the length of the combustion chamber, so while unlikely, a low level of black carbon production is still a possibility. As such several different black carbon emissions scenarios will be considered; a zero BC emissions scenario, a low emissions scenario (6 grams/kg) and the high emissions scenario proposed by Ross (60 grams/kg).

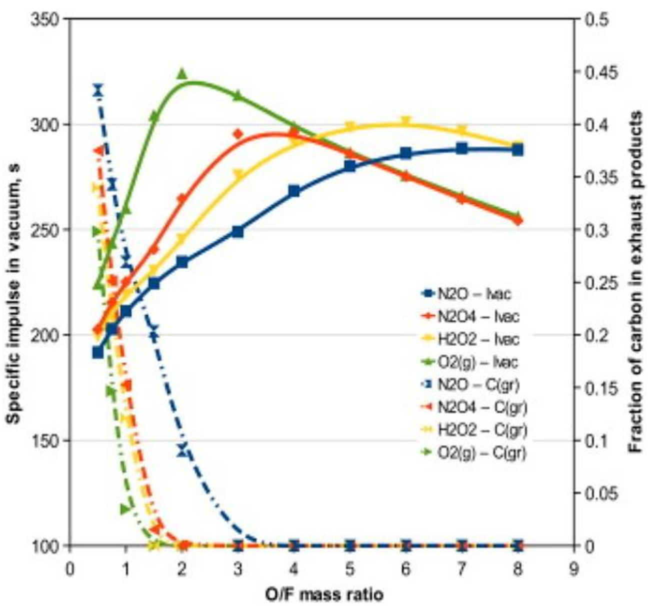

Figure 7 - Specific impulse in vacuum and fraction of carbon vs oxidizer to fuel mass ratio [3].

4.5 Kerosene Manufacturing and Launch

WhiteKnightTwo uses four Pratt & Whitney Canada PW300 engines, which uses the aviation kerosene as a fuel and has specific fuel consumption at cruise of 69.9 kg/kN/h [28, 31]. An LCA of kerosene produced in Thessaloniki refinery found that the combustion of the kerosene contributes 99.5% of the total CO_2 emission for throughout the life cycle, where one kg of kerosene produces approximately three kg CO_2 eq. Contributions from extraction, refinement and transportation are minimal. However, refinement is responsible for a majority of CFC-11 eq. produced throughout the life cycle. The acidification effect shows the most impact from the life cycle of the kerosene, where NO_x emission contributes the most and coming from the use process of the kerosene [32].

Similar to SpaceShipTwo, the emission estimation of WhiteKnightTwo and the carrier aircraft are based on an environmental study conducted in 2012. [25] Table 3 shows the estimated emissions from WhiteKnightTwo and the support aircraft in the upper atmosphere. The emissions from the support aircraft are not considered in the LCA model, since the focus on this report is on the launch vehicle itself.

5. Initial Findings

Advances in the aerospace industry have led to an increase in non-traditional launch methods. The standard method is a ground launch, involving the rocket launching from the ground as part of a multi-stage system. When the first stage runs out of fuel, separation occurs. Significantly reducing mass, and fuel consumption [33]. Examples of this method are Space X's Falcon 9 and Blue Origin's New Shepard. The air launch is a method currently utilized by Virgin Galactic. The concept is to use a conventional ground vehicle, such as airplane, to launch the rocket from high altitude, where atmospheric density is lower compared to sea-level. As such, fuel usage can be reduced as a result of lesser atmospheric drag. 34).

Initial results displayed regard each of the product systems expected emissions outputs with regards to the SSSD Midpoint impact categories, using the GWP 100 global warming potential. It is worth noting that expected transportation emissions as a result of transit between manufacturing facilities and launch sites are not included as of yet, in addition to expected end of life processes and post launch refurbishment costs for each spacecraft.

Table 3 - Estimated emissions WhiteKnightTwo + support aircraft[25)]

Exhibit 4-2. Estimated Emissions to the Upper Atmosphere from WhiteKnightTwo and Support Aircraft (pounds)[a,b]

Description	CO_2	CO	H_2O	VOC	NO_x	SO_x	PM_{10}	$PM_{2.5}$
Emissions per launch								
WhiteKnightTwo carrier aircraft	50,579	26.44	20,093	266.97	200.81	20.77	5.92	5.92
Beech Starship support aircraft	834	45.93	331	14.69	0.51	0.36	ND	ND
Extra EA300 support aircraft	152	72.07	60	3.71	0.16	0.07	ND	ND
Total aircraft, per launch	51,565	144.44	20,485	285.37	201.49	21.19	5.92	5.92
Annual Emissions (30 launches)	1,546,951	4,333	614,542	8,561	6,045	636	178	178

a. Source of emission factors: FAA 2010, IPCC 1999
b. Note: Data have been rounded; CO_2 = carbon dioxide; CO = carbon monoxide; H_2O = water; VOC = volatile organic compound; NO_X = nitrogen oxides; SO_X = sulfur oxides; PM_{10} = particulate matter less than 10 micrometers in diameter; $PM_{2.5}$ = particulate matter less than 2.5 micrometers in diameter; ND = no data available

5.1 New Shepard

Regardless of choice of manufacturing materials, the emissions from New Shepard are largely dominated by the manufacturing of the booster and Crew Capsule, with the rocket launch contributing less than 1% of the overall emissions. Propellant formulation contributes approximately 10% of overall system emissions with electricity consumption a large portion in both the oxygen and hydrogen production processes. This can be attributed to the high energy requirements required to cool and maintain both gases at liquification temperatures. Fig 13 shows the expected emissions for the systems over the course of a single launch, 10 launches and 20 launches, the system does not yet account for the environmental refurbishment cost of the booster and capsule, nor the transportation requirements for fuel and components. 99% of the booster by mass is reusable between launches.

5.1.1 New Shepard Aluminium Matrix Composite

Climate Change - Global Warming Potential 100a	8.80879E5	kg CO...
P casting, aluminium, lost-wax | casting, aluminium, lost-wax | A	3.29151E5	kg CO...
P market for carbon fibre reinforced plastic, injection moulded |	1.66775E5	kg CO...
P electronic component, unspecified, at plant - GLO	8.03866E4	kg CO...
P electricity, high voltage, production RER, at grid - RER	4.95198E4	kg CO...
P titanium production, primary | titanium, primary | APOS, S - GL	3.65476E4	kg CO...
P integrated circuit, IC, logic type, at plant - GLO	3.19133E4	kg CO...
P aluminium alloy production, Metallic Matrix Composite | alum	2.08068E4	kg CO...
P printed wiring board, surface mount, lead-containing surface,	1.56478E4	kg CO...
P casting, steel, lost-wax | casting, steel, lost-wax | APOS, S - RoV	1.50990E4	kg CO...
P turning, aluminium, conventional, average - RER	1.33600E4	kg CO...
P air separation, cryogenic | oxygen, liquid | APOS, S - RER	1.17419E4	kg CO...
P electricity, medium voltage, production DE, at grid - DE	1.06777E4	kg CO...
P market for bisphenol A epoxy based vinyl ester resin | bisphenc	9410.463...	kg CO...

Figure 8 - New Shepard aluminium matrix high impact flows (single launch).

The aluminium matrix composite craft is based largely on similar cryogenic craft, such as the Ariane 5's cryogenic core stage among others. Although not the same, materials and material quantity gives some indication of how New Shepard is composed. The production of New Shepard accounts for approximately 65% of the overall launch emissions, with the crew capsule accounting for another 25%. For both parts of the rocket, aluminium casting via the lost wax method contributes a significant portion of the overall emissions, contributing 35% of the overall emissions from casting of the booster and 10% of the overall emissions from casting of the crew capsule. Overall emissions for the system are 7.141×10^5 kg CO_2 eq. High impact flows are pictured in Figure . The casting of aluminium for the booster accounting for a large portion of the overall emissions, followed by manufacturing of electronics and energy consumption, although one order of magnitude smaller.

Looking at the long-term emissions shown in Fig. 13, from continual use of the launcher the production of propellant becomes roughly equivalent to booster production after approximately 10 launches and becomes the dominant CO_2 eq. producer as the lifetime of the rocket increases. Emissions from launch remain largely insignificant in comparison to the booster, capsule, and propellant production.

5.1.2 New Shepard CFRP

The net emissions for the carbon fibre reinforced polymer scenario are marginally higher than in the aluminium matrix composite craft at 8.82x10^5 kg CO_2 eq. Overall emissions for the booster are largely equivalent, with the substantial impact from aluminium casting replaced with carbon fibre production. This suggests that overall emissions are largely dictated by the craft size and mass, in addition to material selection. As with the aluminium craft variant other significantly contributing flows include the manufacturing of electronic components and minor aluminium lost wax casting from the capsule production. As with the aluminium matrix composite booster, the emissions from propellant production surpass booster and capsule production after roughly ten launches and become the dominant CO_2 contributor. It is worth noting that the model does not yet include refurbishment costs for the booster and as such could affect the overall CO_2 emissions distribution for the system in the long term.

Climate Change - Global Warming Potential 100a	8.82029E5	kg CO...
P market for carbon fibre reinforced plastic, injection moulded |	4.61012E5	kg CO...
P electronic component, unspecified, at plant - GLO	8.03866E4	kg CO...
P casting, aluminium, lost-wax | casting, aluminium, lost-wax | A	7.79889E4	kg CO...
P electricity, high voltage, production RER, at grid - RER	4.95198E4	kg CO...
P titanium production, primary | titanium, primary | APOS, S - GL	3.65476E4	kg CO...
P integrated circuit, IC, logic type, at plant - GLO	3.19133E4	kg CO...
P printed wiring board, surface mount, lead-containing surface,	1.56478E4	kg CO...
P casting, steel, lost-wax | casting, steel, lost-wax | APOS, S - RoV	1.50990E4	kg CO...
P air separation, cryogenic | oxygen, liquid | APOS, S - RER	1.16090E4	kg CO...
P electricity, medium voltage, production DE, at grid - DE	1.06777E4	kg CO...
P market for bisphenol A epoxy based vinyl ester resin | bisphenc	9410.463...	kg CO...

Figure 9 - New Shepard CFRP high impact flows (single launch).

5.2 WhiteKnightTwo & SpaceShipTwo

The emissions from Virgin Galactic's launch vehicle are shown in Figs. 10 - 12. As already stated in section 4, the models are separated into three different black carbon emissions scenarios; zero-BC emissions, low-BC emission (~6 g/kg), and high-BC emission (~60 g/kg). Each scenario is separated into a single launch, ten launch and twenty launch scenarios to show how the emissions from reusable verses disposable parts change over the course of the product life cycle.

5.2.1 Zero-BC emission scenario

In the zero black carbon emissions scenario most of the emissions result from the production of the launch vehicles and kerosene combustion in WhiteKnightTwo. Roughly 35% of the emissions come from vehicle production, which is expected, since the production of both vehicles mostly uses the carbon fiber composites. Moreover, the emissions from the CTN production (over the course of 20 launches) account for approximately 15% of the total emissions from launcher production and are non-negligible. Although, when compared to the whole emissions, especially in the higher-BC scenario, the effect from the CTN production is relatively small. The overall emissions for this scenario are 4.416 x 10^6 kg CO_2 eq. Fig. 10 shows the highly contributing flows for the zero BC emissions scenario. The production for carbon fiber accounts for a significant portion of the overall emissions, followed by electricity consumption and kerosene combustion. These are substantially lower than the production emissions for the CFRP.

Climate Change - Global Warming Potential 100a	1.53571E6	kg CO...
P market for carbon fibre reinforced plastic, injection moulded |	1.12293E6	kg CO...
P electricity, high voltage, production mix | electricity, high volta	1.52717E5	kg CO...
P Launch Event by Propellant Type - Kerosene	7.16528E4	kg CO...
P electricity, medium voltage, production DE, at grid - DE	3.69202E4	kg CO...
P titanium production, primary | titanium, primary | APOS, S - GL	2.66331E4	kg CO...
P electricity, high voltage, production RER, at grid - RER	2.42288E4	kg CO...
P nitrous oxide production | nitrous oxide | APOS, S - RER	1.66475E4	kg CO...

Figure 10. SpaceShipTwo + WhiteKnightTwo high impact flow, zero-BC emission scenario.

5.2.2 Low-BC emission scenario

In the low-BC emission scenario, as shown in Fig. 11, the emission from the N_2O/HTPB is noticeable, and exceeds the production of the WhiteKnightTwo over the course of 20 launches, at approximately 20% of the whole life cycle emissions. The emission from the spacecraft propellant in this scenario is 10 times higher than the zero-BC scenario. The overall emissions for this scenario are 5.358x10^6 kg CO_2 eq.

Climate Change - Global Warming Potential 100a	1.58277E6	kg CO...
P market for carbon fibre reinforced plastic, injection moulded |	1.12293E6	kg CO...
P electricity, high voltage, production mix | electricity, high volta	1.52717E5	kg CO...
P Launch Event by Propellant Type - Kerosene	7.16528E4	kg CO...
P Launch Event by Propellant Type - Hybrid (HTPB/N2O)	5.29842E4	kg CO...
P electricity, medium voltage, production DE, at grid - DE	3.69202E4	kg CO...
P titanium production, primary | titanium, primary | APOS, S - GL	2.66331E4	kg CO...
P electricity, high voltage, production RER, at grid - RER	2.42288E4	kg CO...
P nitrous oxide production | nitrous oxide | APOS, S - RER	1.66475E4	kg CO...

Fig. 11. SpaceShipTwo + WhiteKnightTwo high impact flow, low-BC emission scenario.

Fig. 11 shows the high contribution product flows for a single launch in the low BC emission scenario. The production of CFRP still dominates emissions by an entire order of magnitude, however, emissions from a HTPB launch are comparable to kerosene combustion. Both are still less than electricity consumption from the production life cycle phase.

5.2.3 High-BC emission scenario

In the high-BC emission scenario, as shown in Fig. 12, emissions from overall life cycle are three times greater than the zero-BC scenario, with emissions from N_2O/HTPB combustion increased by 80 times. In this scenario the emissions from the propellant combustion alone are higher than the whole life cycle of the zero-BC scenario. This is expected since a black carbon concentration of 60 g/kg of propellant is substantial for a single launch and would make hybrid fuels one of the highest BC producing fuels in the world. Furthermore, the GWP 100 of BC is tremendous compared to greenhouse gases and emissions. The overall emissions for this scenario are 1.383 x 10^7 kg CO_2 eq. Fig 12 shows high impact flows for the high BC scenario. In the high emissions scenario, the launch emissions for the hybrid fuel are approximately half that of carbon fiber production for a single launch. This makes it the second highest CO_2 eq. emitter in the entire product system for a single launch.

Climate Change - Global Warming Potential 100a	2.00640E6	kg CO...
P market for carbon fibre reinforced plastic, injection moulded |	1.12293E6	kg CO...
P Launch Event by Propellant Type - Hybrid (HTPB/N2O)	4.76609E5	kg CO...
P electricity, high voltage, production mix | electricity, high volta	1.52717E5	kg CO...
P Launch Event by Propellant Type - Kerosene	7.16528E4	kg CO...
P electricity, medium voltage, production DE, at grid - DE	3.69202E4	kg CO...
P titanium production, primary | titanium, primary | APOS, S - GL	2.66331E4	kg CO...
P electricity, high voltage, production RER, at grid - RER	2.42288E4	kg CO...

Figure 12 - SpaceShipTwo + WhiteKnightTwo high impact flow, high-BC emission scenario.

Over 20 launches, it can be concluded that if black carbon emissions are ignored, the contributions from kerosene combustion are the most significant, followed by the production of the launch vehicles. The production of propellant is the third, and finally, with a minimal contribution the combustion of N_2O/HTPB. However, when the effect of the BC is included, the emission from the N_2O/HTPB are greatly increased, depending on the amount of BC emitted. The exact BC emitted in Virgin Galactic's vehicles are unknown, since there are many factors that affect the amount of the BC emitted, such as incomplete combustion, specific impulse in each stage of flight, combustion temperature, nozzle geometry and the O/F ratio.

5.3 Launcher Comparisons

As intended, due to unique launch characteristics Virgin Galactic's launcher can carry a significantly lower fuel volume as compared to Blue Origin's New Shepard. However, despite the lower fuel volume of Virgin Galactic's launch system the propellant choice limits emissions reductions in comparison to New Shepard. Although emissions from propellant production of the LH_2/LOx (7.44 x 10^4 kg CO_2 eq.) are greater than the production of aviation kerosene and HTPB combined (Kerosene: 2.19 x 10^4 kg CO_2 eq. HTPB: 3.89 x10^4 kg CO_2 eq.) the combustion of the kerosene alone is enough to outweigh the production cost of the LH_2/LOx in the zero black carbon scenario. In both the low BC and high BC emissions scenarios this is exacerbated by the increased emissions from HTPB combustion. Regardless of fuel choice, the emissions from high carbon composite usage in both SpaceShipTwo and WhiteKnightTwo far exceed those of Blue Origin's counterpart, in both the aluminium metal matrix composite and CFRP scenarios. In comparison however, the carbon fiber concentration by mass in the New Shepard CFRP model is substantially lower than that of New SpaceShipTwo and WhiteKnightTwo. Given that in the New Shepard CFRP model this is the product flow with the highest impact an under-estimate could mean that emissions from the CFRP model are closer to those of Virgin Galactic's launch system.

The results of this comparative study are illustrated in Fig. 13 for various scenarios.

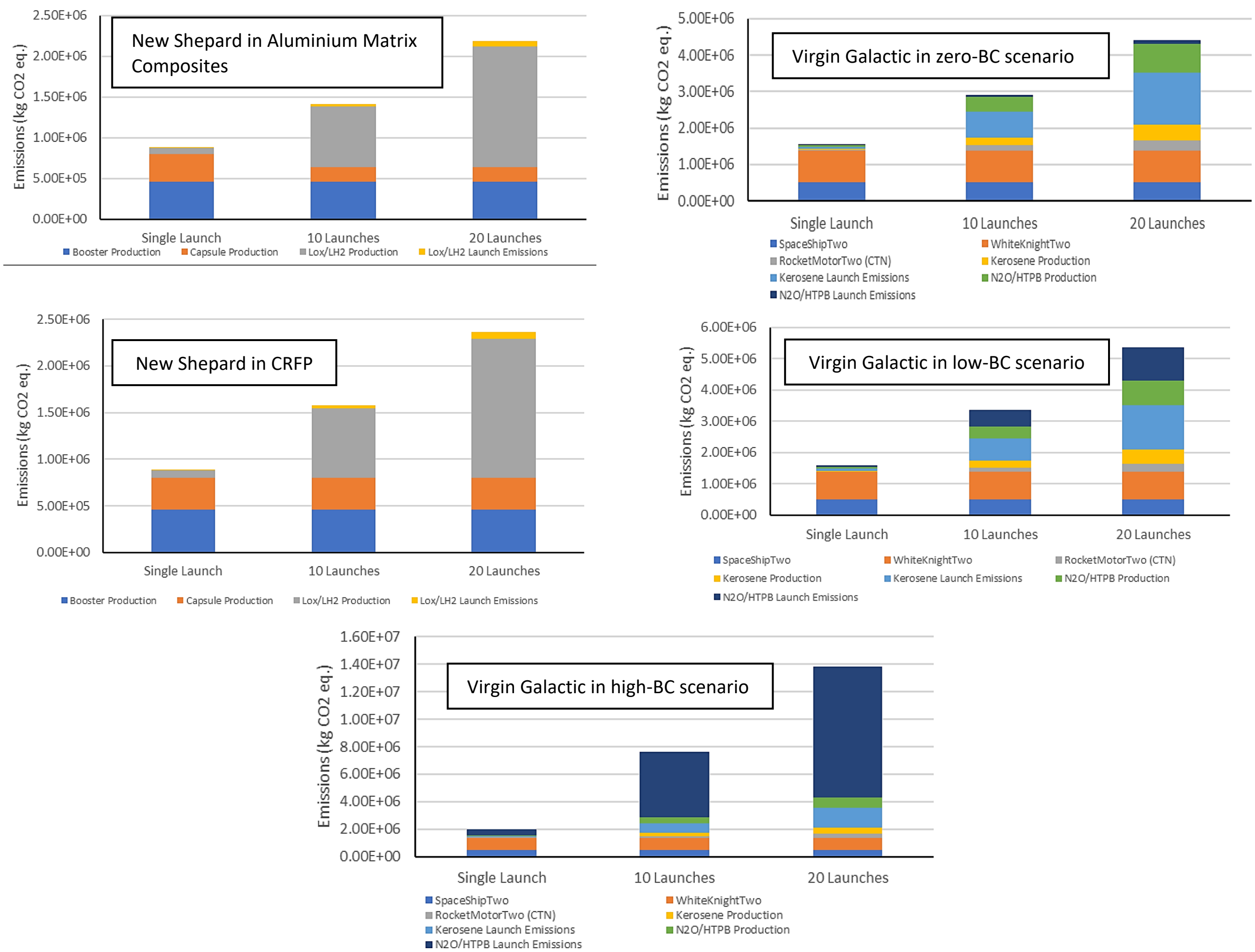

Figure 13 - Emissions for Blue Origin and Virgin Galactic for different scenarios.

6. Discussion and Conclusions

The data presented in section 5 shows that there are several high impact flows that dictate the impact on product life. In sub-orbital launchers using CFRP or aluminium metal matrix composites the cost of production is substantial in comparison to launch emissions and propellant manufacturing. When using non-polymer-based materials launcher production processes contribute significantly to emissions than the production of the materials themselves. Comparing New Shepard to SpaceShipTwo/WhiteKnightTwo the emissions from high CFRP usage in Virgin's launch system far exceeds that of New Shepard for both the

CFRP and aluminium metal matrix composite. However, in the CFRP model the proportion of carbon fiber composites is substantially lower than in Virgin Galactic's launch system which could account for the large emissions disparity despite using the same material. When considering longer term usage propellant production and combustion becomes more substantial, this is standard for most transportation-based life cycle assessments. As the propellant used by New Shepard is relatively low impact, the propellant formulation contributes most of the emissions for the system in both scenarios. Virgin Galactic's launch system similarly sees most of the emissions produced by propellant combustion and production in the long term, particularly for the low and high black carbon production scenarios where N_2O/HTPB production and combustion alone contribute a substantial proportion of the emissions. In the high black carbon emissions scenario N_2O/HTPB combustion dwarfs all other contributors when we consider the 20-launch time frame. Currently the emissions for Virgin Galactic's system far outweigh those of New Shepard regardless of the scenario. Refurbishment costs not been evaluated, although it is likely they are roughly equivalent for the purposes of comparison. Furthermore, transportation of launchers, componentry and propellant has not been included in the model. This is particularly important in Virgin Galactic's case as the transportation of the motor CTN from the manufacturing facility to the launch site has the potential for emissions contributions, especially when long term scenarios are considered.

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8. Copyright Statement

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