THE RELATIONSHIP BETWEEN LIGHT-WEIGHTING WITH CARBON FIBER REINFORCED POLYMERS AND THE LIFE CYCLE ENVIRONMENTAL IMPACTS OF ORBITAL LAUNCH ROCKETS

A DISSERTATION
Presented to
The Academic Faculty

by

Yuriy Alexander Romaniw

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
in the School of Mechanical Engineering

Georgia Institute of Technology
December 2013

The Relationship between Light-Weighting with Carbon Fiber Reinforced Polymers and the Life Cycle Environmental Impacts of Orbital Launch Rockets

Approved by:

Dr. Bert Bras, Advisor
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Jonathan S. Colton
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Kyriaki Kalaitzidou
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Alan W. Wilhite
School of Aerospace Engineering
Georgia Institute of Technology

Dr. John D. Muzzy
School of Chemical and Biomolecular Engineering
Georgia Institute of Technology

Dr. John M. Griffith
The Boeing Company (retired)

Date Approved:

To all those that stood in my way.

TABLE OF CONTENTS

LIST OF TABLES

List of Figures

SYMBOLS AND ABBREVIATIONS

A_{base}	cross sectional area of the rocket's base
AP	ammonium perchlorate
APCP	Ammonium Perchlorate Advanced Propellant
$A_{surface,tank}$	surface area of propellant tank
CFRP	carbon fiber reinforced polymer
D	rocket diameter
DMA	dimethylamine
EP	epoxy
f_{inert}	inert mass fraction, also *IMF*
g_0	acceleration due to Earth's gravity at sea level
GEM	Graphite Epoxy Motor (typ. followed by diameter in inches, e.g.: GEM-40)
HM	high modulus
HS	high strength
HT	high temperature
HTPB	hydroxyl-terminated polybutadiene
IM	intermediate modulus
IMF	inert mass fraction, also f_{inert}
IRFNA	see also *RFNA*, inhibited red fuming nitric acid
I_{sp}	specific impulse
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LEO	low Earth orbit
LH2	liquid hydrogen
LOX	(also: LOx) liquid oxygen

LT	low temperature
m_{engine}	engine mass
MER	mass estimating relationship
m_{fuel}	fuel mass
m_{inert}	inert or structural rocket mass
MMH	monomethylhydrazine
m_{ox}	oxidizer mass
m_{pl}	payload mass
m_{prop}	propellant mass
$m_{prop,RCS}$	reaction control system propellant mass
MR	mass ratio
m_{tot}	total or gross rocket mass
O/F	oxidizer to fuel ratio
Δp	impulse or change in momentum
PAN	polyacrylonitrile
PBAN	polybutadiene acrylonitrile
RCS	reaction control system
RFNA	see also *IRFNA*, red fuming nitric acid
r_{orbit}	radius of orbit from Earth's center
RP-1	(also: *RP1*) Rocket Propellant-1, or Refined Petroleum-1
PRSM	Parametric Rocket Sizing Model
SRB	solid rocket booster
SSSRB	Space Shuttle Solid Rocket Booster
T	thrust
UDMH	unsymmetrical dimethylhydrazine
v_{circ}	circular orbital velocity

$V_{prop,RCS}$	reaction control system propellant volume
V_{tank}	propellant tank volume
ΔV	change in velocity
μ_{earth}	gravitational parameter of Earth

CHEMICAL FORMULAE

$(CH_3)_2NH$	dimethylamine (Cicerone, Stedman et al.)
CH_3OH	methanol
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
HCl	hydrogen chloride (hydrochloric acid if aqueous)
N_2	nitrogen
N_2O_4	nitrogen tetroxide, or dinitrogen tetroxide
$NaOH$	sodium hydroxide
NH_2Cl	chloramine
$NH3$	ammonia
O_2	oxygen

SUMMARY

A study was undertaken to determine if light-weighting orbital launch vehicles (rockets) improves lifetime environmental impacts of the vehicle. Light-weighting is performed by a material substitution where metal structures in the rocket are replaced with carbon fiber reinforced polymers (CFRP's). It is uncertain whether light-weighting the rocket in the same way as traditional vehicles are light-weighted would provide similar environmental benefits. Furthermore, the rocket system is significantly different from traditional vehicles and undergoes an atypical lifecycle, making analysis non-trivial. Seventy rocket configurations were sized using a Parametric Rocket Sizing Model (PRSM) which was developed for this research. Four different propellant options, three staging options, and eighteen different lift capacities were considered. Each of these seventy rockets did not include CFRP's, thus establishing a baseline. The seventy rockets were then light-weighted with CFRP's, making a total of seventy pairs of rockets. An environmental Life Cycle Assessment (LCA) was performed on each of the rockets to determine lifetime environmental impacts. During the Life Cycle Inventory (LCI), a Carbon Fiber Production Model was developed to determine the environmental burdens of carbon fiber production and to address issues identified with carbon fiber's embodied burdens. The results of the LCA were compared across all rockets to determine what effects light-weighting had on environmental impact. The final conclusion is that light-weighting reduces lifetime environmental impacts of Liquid Oxygen-Rocket Propellant 1 and Nitrogen Tetroxide-Unsymmetrical Dimethylhydrazine rockets, while it likely benefits Liquid Oxygen-Liquid Hydrogen rockets. Light-weighting increases lifetime environmental impacts of Solid Propellant rockets.

1 INTRODUCTION

1.1 Sustainability and Environmental Stewardship

According to the United States Environmental Protection Agency (EPA), "Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment."(Environmental Protection Agency 2013) Since we are dependent on our natural environment, it is in our best interest to preserve its health. At some level, we *must* interact with the environment, consuming resources and returning byproducts of our existence. This interaction must be done in such a way that we do not jeopardize our future with careless consumption and wasteful activities in the present. This is where the notion of *sustainability* comes into play.

The EPA defines sustainability in the following way (Environmental Protection Agency 2013):

> *Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations.*

Sustainability is not an absolute. However, we can strive to become *more* sustainable with our activities, constantly pushing the eventuality further and further into future. Though we may not be sustainable *ad infinitum*, we can achieve a certain level of effective sustainability, where the future cessation of activities is a result of choice rather than necessity.

In order to become more sustainable, we must manage our activities to minimize negative environmental impacts while still meeting the requirements of our society. It is our responsibility to investigate more environmentally sustainable alternatives, implementing them as often as possible. Realizing that there is often a cost-benefit tradeoff with many of these alternatives, we must ensure that there is net positive improvement over the entire life of the system.

Environmentally preferable alternatives do not have to compromise functional performance. Rather than restricting activities or expectations, skillful engineering of man-made systems can be used to reduce impacts while maintaining or improving performance. Systems can still achieve their intended objectives while using environmentally preferable energy sources, using materials with lower environmental impacts, achieving higher levels of efficiency, and usefully recovering byproducts.

Many common systems have already been re-engineered to become more sustainable. Products, like automobiles and airplanes, have been made more efficient through the use of alternate materials. The environmental impacts of these systems have been reduced without compromising performance, and they have become a model for other systems on how to become more sustainable.

A common approach many systems take to mitigating environmental impacts is called *light-weighting*. The fundamental principle behind light-weighting is that the mass or weight of the system is reduced, making it more efficient during use. The system requires less energy during operation, and with a lower energy demand, less fuel is consumed and fewer emissions are produced. The relationship between light-weighting and environmental impacts of systems like automobiles and airplanes is fairly well understood, as is discussed in further detail in Chapter 2.

1.2 Cause for Concern with Some Systems

Some systems may not have the economies of scale that automobiles and airplanes enjoy. These systems can be costly, complex, and have difficult to achieve objectives, making them driven by functional performance rather than environmental performance. However, this does not mitigate or remove our environmental responsibility to make producing, operating, and disposing of these systems more sustainable.

One such performance driven system is the rocket-based orbital launch platform. When compared to other vehicles, like automobiles and airplanes, there has been relatively little done to address the environmental impacts of a rocket. Rockets are optimized for many factors, but environmental performance is currently not one of them.

At present, environmental impacts associated with rockets are virtually negligible when compared to the environmental burdens of other systems and industries. This is due to the infrequency with which large rockets are launched when compared to the frequency and prevalence of use of other vehicles. However, the literature review in Chapter 2 shows that despite currently having a small environmental impact, propellants, space debris, waste in impact zones, and damage in launch areas have already been the subject of some study. Despite this existing literature, information is limited and found in pieces. Neither general nor detailed assessments are available about the expected performance of the *entire* rocket system over its *life cycle*. Further investigation is required.

In the long term, environmental burdens from rockets may not always be negligible. As environmental improvements occur in other industries, the relative magnitude of the environmental burdens associated with rockets increases if rocket environmental burdens remain unaddressed. This, coupled with an increase in the frequency of rocket launches, can make the environmental impacts of rockets more important to study and understand.

Though the increase in relative magnitude of rocket impacts can be disputed with improvements in other industries, there is strong evidence to suggest that rocket launches will become more frequent in the future. (Federal Aviation Administration 2012) Whereas six decades ago only the United States and the Soviet Union were launching orbital rockets, at a combined rate of one every few weeks or months, today there are launches scheduled virtually monthly from Kennedy Space Center, FL alone. Multiple nations are also involved in constructing and launching their own orbital rockets. The variety of payloads that are to be launched on large rockets is virtually limitless, creating an indefinitely growing demand for rocket technology. With the emergence of Space Tourism, launches may become weekly, if not daily events. The demand is reflected by the emergence of multiple private companies that are developing their own launch systems. These include, but are not limited to United Launch Alliance (joint Boeing and Lockheed Martin Venture), Space Exploration Technologies Corporation (SpaceX), Blue Origins, Orbital Sciences Corporation, The Spaceship Company (Scaled Composites and Virgin Galactic), and Starchaser Industries.

Looking more closely into some of these emerging companies, issues that affect long term sustainability start becoming evident. The Falcon 9 rocket built by SpaceX uses refined kerosene as a fuel.(SpaceX 2009) Kerosene is distilled from petroleum, which is not a renewable resource, and it produces environmentally detrimental emissions, like carbon dioxide and carbon monoxide, when burned (Simonsen 2009). Substituting the kerosene fuel with liquid hydrogen (another common fuel used in rockets) at first seems to mitigate the environmental burdens of the rocket. Liquid hydrogen is a much more efficient rocket propellant and produces only water vapor when burned. However, liquid hydrogen is produced in large quantities by cracking hydrocarbons like methane, naphtha, or coal, which also are not renewable resources. (Caras 1963) Furthermore, liquid hydrogen is less dense than kerosene, requiring a physically larger rocket, and is a cryogenic fuel, which requires more significant insulation. This highlights how environmental cost-benefits of some alternatives for rockets are more complex than they appear on the surface. It is difficult to determine which alternative is environmentally preferable without either further analysis or models that can accurately predict behavior.

The exact trend of increasing demand for large rocket technology is not specifically known, but it is outside of the scope of this research to predict how large and the speed with which the rocket industry can grow. It is being asserted that the industry *can* and is *expected* to become larger and that environmental impacts *can* become significant. It is important to determine the potential environmental impacts of rocket systems through their life cycle, and what affect certain design alternatives have on these impacts.

This research focuses on light-weighting a rocket and the potential environmental benefits this may have. Light-weighting through the use of carbon fiber composites has been used in other vehicles to successfully mitigate environmental burdens by reducing energy consumption during the use phase. This research seeks to determine if a similar relationship between light-weighting and environmental impacts exists for rockets.

Proper understanding of how the system interacts with the environment will help better predict environmental impacts so that *preventative* measures may be taken.

1.3 Description of the System of Interest

This research focuses on the impacts orbital launch rockets have on the environment. Specifically, the way in which environmental impacts change with light-weighting of the rocket with carbon fiber composites is of interest. Light-weighting can be accomplished in multiple ways. This research centers on light-weighting a rocket by changing the materials used in the rocket's structure. Light-weighting a rocket's structure reduces the amount of propellants needed to achieve a particular mission, hopefully reducing lifetime environmental impacts.

Replacing metal structures with carbon fiber composites is one common way to light-weight a system. Environmental benefits of light-weighting automobiles with carbon fiber composites have been studied extensively in literature. (Zushi, Takahashi et al. 2003; Van Acker, Verpoest et al. 2009; Duflou, Sutherland et al. 2012; Suzuki, Odai et al. undated) It is of interest whether a rocket's life cycle impacts improve with light-weighting in the same way, or whether there is some other trend or relationship that describes how the environmental behavior of rockets changes. Though environmental stewardship is currently not a driving motivation for light-weighting a rocket, the life cycle environmental impacts must be determined so that steps can be taken to better understand and improve system sustainability.

The rockets considered here are assumed capable of launching a payload into low Earth orbit (LEO), which can represent orbits of less than 2,000 km (1,200 miles) in altitude. In this research, an altitude of 400 km is assumed, approximately representing the altitude of the International Space Station. The term *orbital launch vehicle* is used here to mean the types of rockets capable of achieving this orbit or higher, distinguishing them from smaller rockets such as military rockets, ballistic missiles, and sounding rockets.

A rocket is a means of accelerating a payload from an initial (likely known) velocity to a final desired velocity. Most fundamentally, a rocket changes the momentum of a payload by delivering an impulse. Impulse is provided by applying a thrusting force on the payload over some finite amount of time. If the payload mass is known or given, then the rocket's performance can be measured by the total change in velocity (ΔV) the rocket can provide. As is discussed later, the functional unit used in analyzing the lifetime impacts of a rocket is **1 kg payload to LEO**. Specifying payload mass brings insight into a rocket's total size, and ΔV is defined by indicating that the desired objective is LEO.

The ΔV is delivered to the payload mass by applying thrust over time. Thrust can be generated a number of different ways. Rockets considered here are assumed to generate thrust by using chemical propulsion. Specifically, thrust is assumed generated by combining two propellants, a fuel and an oxidizer, and allowing them to react in a combustion process, generating pressure in the combustion chamber. The pressurized combustion products are accelerated through a converging-diverging nozzle, producing thrust in the process.

The rockets being assessed in this analysis are considered to have three fundamental components:

- The Payload
- The Propellants
- Inert Components

For the purposes of this analysis, the payload is assumed to be only a mass. The environmental impacts of the payload are neglected. These impacts may be significant in their own right, but the choice is made here to allocate all of those impacts to the life cycle of the payload and not to that of a rocket. From the rocket's perspective, it fundamentally doesn't matter *what* the payload is, only that there *is* a payload and it has some mass that must be accelerated.

Propellants are consumed to generate the thrust required to deliver the desired or ΔV to the payload mass. Only the propellants actually consumed during use are placed in this category. A rocket can carry excess propellants for a variety of safety and reliability reasons. This excess is not included with the useful propellants and is rather grouped with the rest of the rocket's inert mass.

The inert components of the system include all structural components of the rocket that are not the payload or useful propellants consumed during acceleration of the payload. As mentioned above, this includes excess propellants in reserves, residuals, and ullage (propellant tank volume not filled with liquid propellants). Functionally, this excess is dead weight and does not contribute to the rocket's ΔV. Under ideal circumstances, the inert mass of the system would approach zero and the rocket would only carry the minimum amount of propellants required to deliver the desired ΔV to a payload.

1.4 Motivation for Research and Problem Statement

Determining the relationship between using carbon fiber composites for the purpose of light-weighting and life cycle environmental impacts of a rocket is non-trivial. The relationship is more complicated than simply saying that a lighter rocket consumes less propellant, and is therefore environmentally preferable. This sort of generalization seems to be adequate for environmental analysis of other systems, but rockets are not sufficiently similar to these other systems to assert the same conclusion for the same reasons. The large gaps in the existing body of work make it difficult to confidently state the relationship between light-weighting a rocket and environmental impacts. Complicating factors include issues like rockets having an atypical life cycle, rockets carrying their entire use phase supply of not only fuel but oxidizer, and rockets consuming a variety of exotic propellants.

The problem can be stated as follows:

> *There is currently no clear relationship between the light-weighting of rockets and the resulting change (if any) in a rocket's life cycle environmental impacts.*

The primary goal of this research is to determine this relationship and how certain other design factors affect this relationship.

1.5 Research Questions and Prediction

To address the uncertainty as to the relationship between light-weighting rockets and life cycle environmental burdens, two research questions are formulated. The answers to these questions expand the understanding of the role light-weighting materials play in the life cycle impacts of a rocket system. The first question seeks to determine if light-weighting has a net environmental benefit as it does for other systems:

> *<u>Research Question 1:</u> Does light-weighting a rocket with carbon fiber composites lead to a net reduction in lifetime environmental impacts?*

Light-weighting automobiles and airplanes benefits the environment by reducing the fuel load required by these systems during their use phase. Rockets can use a variety of propellants and propellant combinations that may change the degree to which light-weighting changes impacts on the environment. Additional uncertainty in this relationship can be caused by other design factors, such as the number of stages the rocket has and the rocket's overall size. The first question can be expanded to account for this variability:

> *Research Question 2:* *How does the relationship between light-weighing with carbon fiber composites and environmental impacts change when different rocket configurations are considered?*

Other vehicles are heavily use phase dominated in terms of their environmental burdens, and as a result light-weighting's benefits in these other vehicles are realized most strongly in the use phase. Both the upstream and use phase environmental burdens can change drastically with different rocket propellants. Assuming light-weighting has a net benefit on a rocket's environmental burdens, it is unclear whether these benefits would be realized in the use phase, as with other vehicles, or elsewhere in the life cycle. The answer may change as the propellants change, so it is important to not only identify whether light-weighting has a net lifetime reduction of environmental burdens but also where during that life cycle are those benefits realized.

There are a large number of possible propellant combinations. This research narrows the scope to a select group of common propellants. In this way, generalized behavior for the majority of systems can be identified before dedicated, case-specific analysis occurs.

General sizing calculations indicate that reducing inert mass of a rocket has a compounding effect that reduces the required propellant load, further reducing inert mass. Light-weighting a single component leads to an initial reduction in propellant load, which leads to further reductions in inert mass since less propellant needs to be contained and lifted, which in turn further reduces propellant load, and so on (to a limit). It is also historically known that the ratio of propellants to inert mass is very high, such that propellant mass is on the order of 5-10 times higher than inert mass. This indicates that the rocket's lifetime environmental burdens are likely dominated by propellant consumption, though perhaps not by such a large margin as for other vehicles. Furthermore, based on the amount of literature that focuses on the environmental burdens of propellant use (discussed in detail in Chapter 2), it is expected that environmental benefits from light-weighting are realized during the use phase.

This research attempts to prove that rockets behave similarly to automobiles and airplanes with respect to changes in environmental impacts due to light-weighting.

1.6 A Structures Problem or a Propellants Problem?

Is the relationship between light-weighting a rocket and environmental burdens a structures problem or a propellants problem? For other vehicles, light-weighting is not structurally motivated. Light-weighting seeks to reduce environmental impacts by reducing fuel consumption. The environmental issue is with the fuel and not the structure, making it a fuel problem. The same is assumed for rockets. Light-weighting may change the structure of the rocket, but it is ultimately addressing an issue related to the propellants.

Other vehicles reduce environmental burdens by reducing fuel consumption because fuel consumption dominates lifetime impacts. Any increase in impacts caused by selecting a different material to light-weight the system is greatly overshadowed by the benefits of fuel savings. It is not clear whether propellants dominate a rocket's lifetime impacts because there is not enough literature to support this conclusion with confidence. During the course of this research, it may be found that a rocket's lifetime impacts are dominated by the structure and not by propellants. In this case, the environmental issue would be a structures problem, though this is not expected to be the case.

1.7 Research Framework and Validation Approach

Possible rocket configurations are effectively limitless. This research must restrict the number of possible configurations considered so that a relationship can be established in a timely manner. Though a limited number of possible configurations are chosen for analysis, these configurations are representative of and can provide great insight into the majority of rocket systems currently in use.

Configurations are limited to choose from a small list of propellants, staging options, and payload sizes. The exact choices under consideration are described in detail in Chapter 4. An environmental *Life Cycle Assessment* (LCA) is performed on each of the different configurations for each payload mass to determine environmental impacts of the rocket. Each of the rockets is then light-weighted by assuming part of its mass is reduced by some factor and the material replaced with carbon fiber composites. The assessment is repeated on each of the light-weighted rockets and the results are compared.

Comparing the life cycle analysis results of an un-lightened rocket, referred to here as the *baseline* rocket, to a light-weighted rocket is expected to answer the first research question, determining if there is indeed a lifetime reduction in environmental impacts with light-weighting. Comparing baseline rockets and light-weighted rockets with different propellant combinations, overall sizes, and different staging options hopefully answers the second question. Furthermore, an LCA helps identify where in the life of each rocket the environmental benefits (if any) of light-weighting are realized.

The hope is to identify a predictable trend or relationship. Such a trend or relationship is necessary to conclusively answer the research questions.

1.8 Contributions of Research

This research has contributions both to academia and to industry:

- First determination of environmental benefits of light-weighting rockets
- First environmental LCA of generalized orbital launch rockets
- Framework for future environmental assessment of rockets
- Insight into rocket environmental life cycle
- Information for preemptive actions on environmental stewardship

In literature, there is no broad understanding of the environmental life cycle of a rocket. Academically, this research performs the first detailed environmental LCA's of orbital launch platforms. The results give insight into a wide range of different rocket systems, where any current assessments on rockets only give limited and specific insight into the particular system they are assessing. In the course of performing these environmental LCA's, this research develops a life cycle modeling framework for performing such an environmental assessment on rockets. This framework can be used as a foundation for future research into this field. This research is the starting point from which future work can grow.

The findings of this research can also help achieve a more sustainable space industry. Rockets are the primary means of launching payloads into Earth orbit and beyond. In order to maintain access to space with current technology, the sustainability of a rocket must be known so that more sustainable designs can be continued and less sustainable rocket configurations can be avoided. This helps ensure the long term survivability of any stakeholder in the industry of manufacturing, purchasing, or launching rockets.

This analysis can help identify parts of a rocket's life cycle that are particularly sensitive to environmental scarcity. Resource scarcity can have long term impacts on the availability of raw materials that are required to produce propellants and structures. Rocket operations can be, and already have been (United States General Accounting Office 1992) restricted due to environmental regulatory compliance. Scarcity does not have to be the result of rocket activities, and insight into the environmental inputs and outputs to a rocket's life cycle can indicate where sensitive resources are being consumed.

1.9 The Structure of This Dissertation

This dissertation begins by performing a thorough literature review in Chapter 2. This review discusses background information, fundamentals of the system of interest, and existing work that is relevant to the research being performed here. Next, Chapter 3 discusses the general approach and methodology followed during the course of this research.

Chapter 4 defines the rocket system under consideration in this assessment. This chapter outlines, in detail, the specific propellants, payloads, and number of stages that are considered.

Chapters 5 through 8 detail the *Life Cycle Inventory* (LCI) for the various parts and processes of the rocket. Chapter 5 focuses specifically on propellants. Chapter 6 focuses specifically on structural materials and manufacturing processes. Chapter 7 details the specific carbon fiber composite used during light-weighting. Finally, Chapter

8 looks at the inventory for the overall rocket life cycle and how this information is modeled in an LCA software tool.

Chapter 9 details the results of the life cycle impact assessment. This chapter provides the first insight into the answers to the two research questions. However, additional analysis must be performed to ensure these conclusions are valid. Chapter 10 discusses the results of an uncertainty analysis that helps support the conclusions obtained in Chapter 9.

Chapter 11 performs separate analyses assuming different scenarios. These analyses are not necessary to answer the two research questions, though they can provide additional insight into a rocket's life cycle impacts. This chapter is useful in that it helps support some of the assumptions made throughout the dissertation and to ensure that no major factors were excluded or overlooked.

Finally, this dissertation concludes with Chapter 12. The two research questions are answered and the overall effects of light-weighting are discussed in detail.

The overall structure of this dissertation is shown graphically in Figure 1.

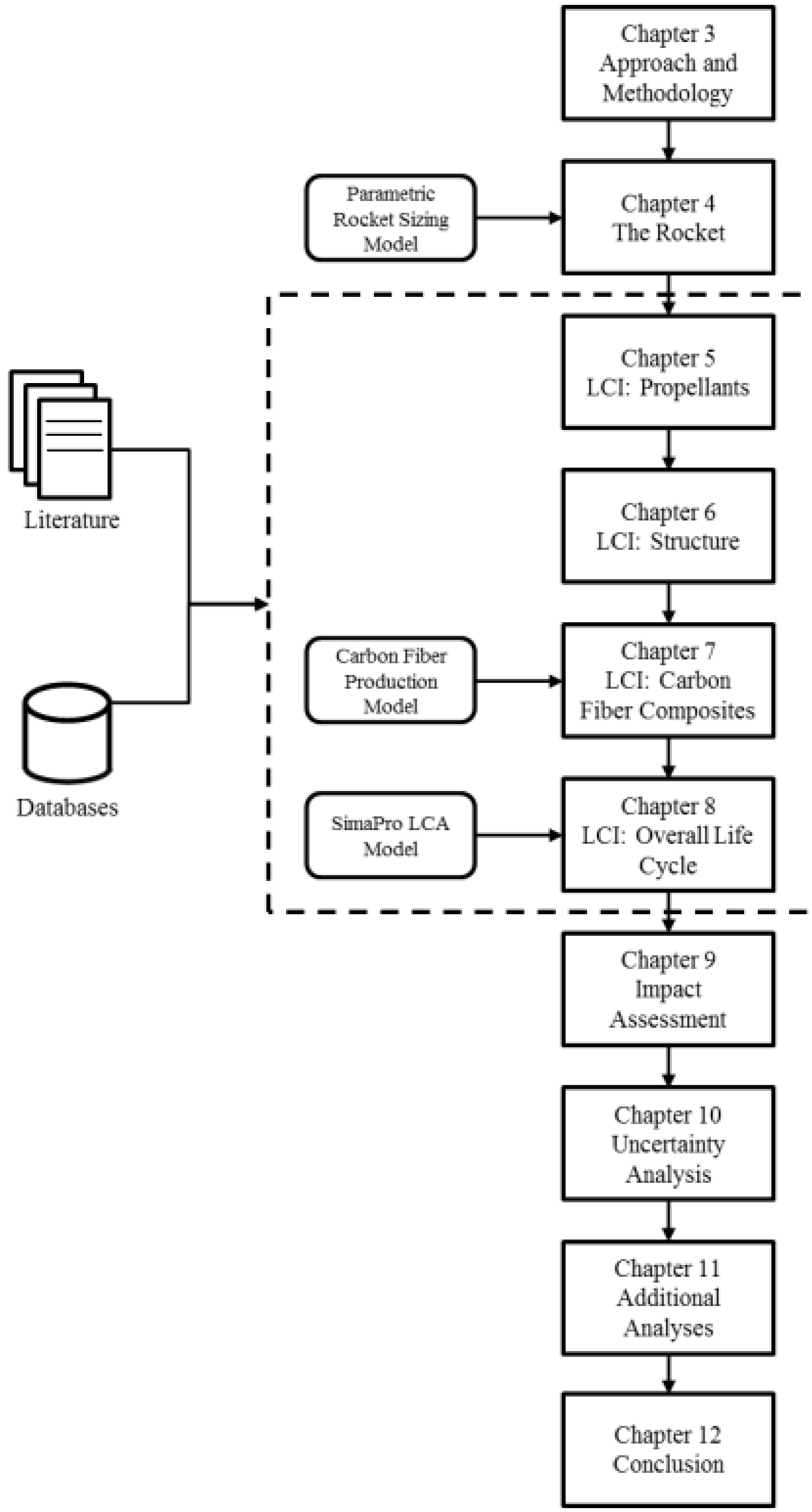


Figure 1: General structure and flow of this dissertation

2 BACKGROUND AND LITERATURE REVIEW

2.1 Structure of the Literature Review

This literature review begins with some background and an overview of some rocket fundamentals. Next, a background on Life Cycle Assessments is presented, followed by a discussion of existing literature relating to a rocket's overall life cycle and specifically to propellants and structural materials. Then, this chapter discusses in detail the historically established benefits of light-weighting with carbon fiber composites, focusing on what is currently known about the carbon fibers themselves. Specifically, issues surrounding the environmental burdens of the carbon fibers during production are discussed. This chapter ends with concluding remarks.

The purpose of this literature review is to explore and discuss any existing research and information that may be relevant to this research. It also helps put the work presented in this dissertation in perspective relative to the greater body of current knowledge on this topic.

2.2 Overview of Rockets

2.2.1 Fundamentals of Rocket Propulsion

Two types of propellants are considered here: liquid and solid. Liquid propellants have both a liquid fuel and oxidizer that are stored separately until mixed in the combustion chamber. Solid propellants have the fuel and oxidizer bound together in a solid grain. Liquid propellants produce thrust using an *engine*, while the term *motor* is used for solid propellants. (Humble, Henry et al. 1995) Hybrid rocket propulsion systems that combine a liquid oxidizer with a solid fuel have been used in real world systems (Scaled Composites undated), but these fall outside of the scope of this analysis.

Propulsion system efficiency can be measured using *specific impulse* (I_{sp}). Specific impulse relates the thrust generated due to the propellant consumption rate and can be defined as "the total impulse per unit weight of propellant" (Sutton and Biblarz 2001), giving I_{sp} the units of *seconds*. The relationship between thrust and I_{sp} can be seen in Equation 1.

$$F_T = I_{sp}\dot{m}_{fuel}g_0 \qquad (1)$$

According to this equation, as I_{sp} goes up, so does thrust. Similarly, for a given level of thrust, a propulsion system with higher I_{sp} consumes propellants less quickly, indicating that it will consume a smaller mass of propellants to launch a particular rocket. (Humble, Henry et al. 1995; Sutton and Biblarz 2001)

In practice, it is found that different propulsion systems typically have different T/W ratios. Solid propellants typically have high T/W because the simplicity of the motor means that fewer components and less structure is needed. In the case of liquid engines, factors like volumetric density of propellants, I_{sp}, and engine thrust determine engine weight. For the liquid propellants considered in this research, it is found that LOX/LH2 engines have the highest T/W ration, while LOX/RP1 have a lower T/W, and the N2O4/UDMH have the lowest T/W. This can be seen in Figure 2.

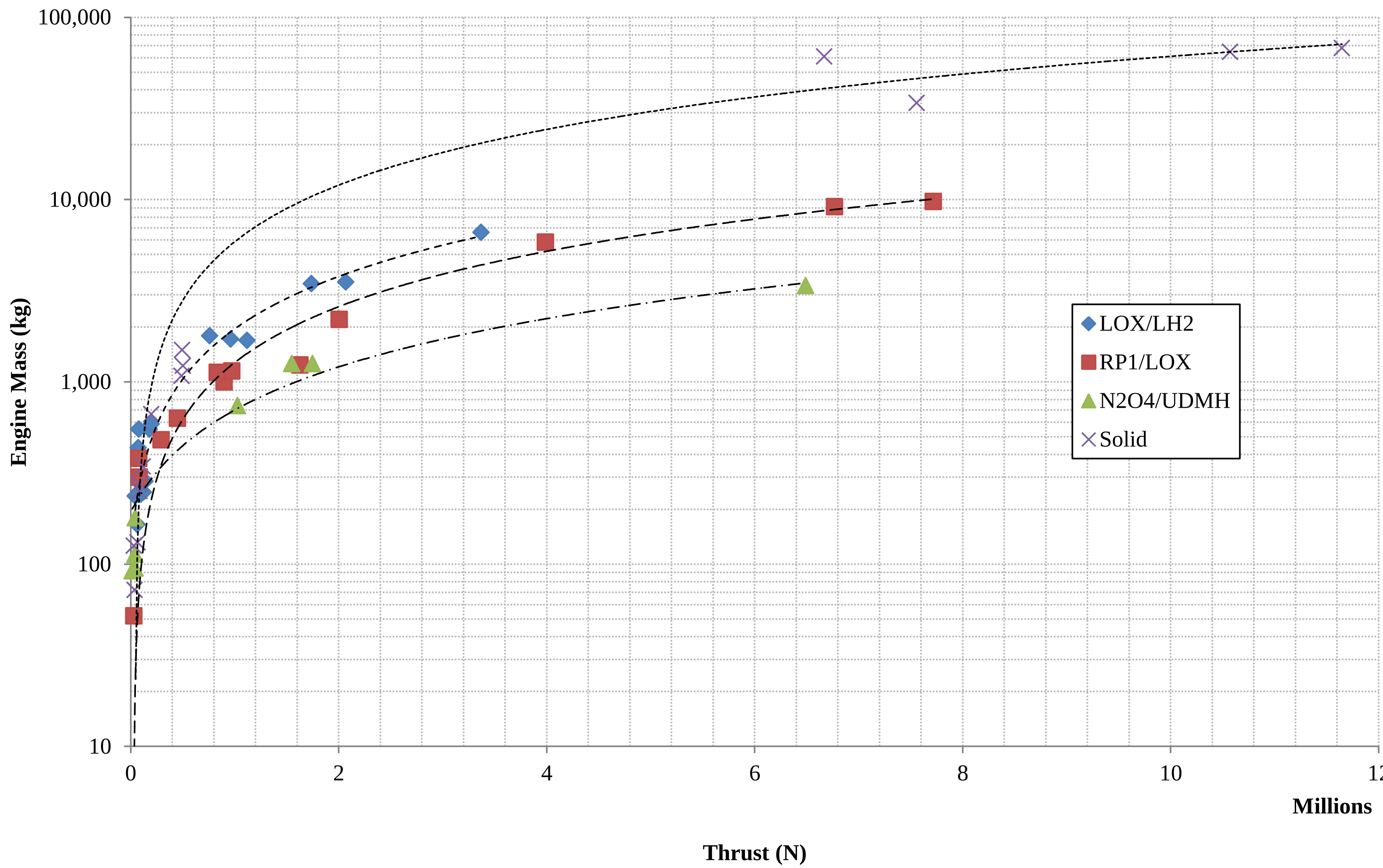


Figure 2: Engine mass as a function of thrust for a variety of different propellant combinations

There are many different liquid propellant combinations, of which some common combinations are shown in Table 1.

Table 1: Liquid propellant combinations (Bruhn, Orlando et al. 1967)

		Fuel						
		Methane	Hydrazine	Hydrogen	UDMH	RP-1	Aerozine 50	MMH
Oxidizer	Oxygen	**X**	**X**	**X**	**X**	**X**		
	Fluorine		**X**	**X**				**X**
	Nitrogen Tetroxide		**X**		**X**		**X**	**X**
	IRFNA					**X**	**X**	
	Hydrogen Peroxide					**X**		**X**

The liquid propellants used have not changed much over the decades. Each propellant combination has a particular advantage and different propellants are used based on application. For instance, some of the different propellants used by the Apollo program to get men to the Moon and back are seen in Table 2. Considerations for selecting one propellant combination over the other include theoretical thrust, I_{sp}, storability of propellants, density of propellants, simplicity of ignition, and reliability of operation, engine thrust to weight (T/W) ratio, among other factors.

Table 2: Various propellants used during the Apollo Program according to application (Bruhn, Orlando et al. 1967; Humble, Henry et al. 1995; Sutton and Biblarz 2001)

Application	Propellants
Saturn V First Stage	LOX/RP-1
Saturn V Second Stage	LOX/LH2
Saturn V Third Stage	LOX/LH2
Service Module	N2O4/A 50
Reaction Control System	N2O4/MMH
Launch Escape System	Solid
Lunar Descent Stage	N2O4/A 50
Lunar Ascent Stage	N2O4/A 50
Lunar Module RCS	N2O4/A 50

This research focuses only on propellants used to achieve orbit in the rocket itself. Some consideration is given to *reaction control system* (RCS) propellants, but they end up being a small influence on the rocket's lifetime environmental impacts and are used primarily for sizing purposes.

To limit the scope of this research, three commonly used liquid propellant combinations and one solid propellant are considered. The liquid propellants are liquid oxygen (LOX) and liquid hydrogen (LH2), LOX and Rocket Propellant 1 (alternatively RP1 and RP-1), and nitrogen tetroxide (N2O4) and unsymmetrical dimethylhydrazine (UDMH). The LOX/LH2 combination is favored for its high I_{sp}. However, both LOX and LH2 are cryogenic and are non-storable. Furthermore, LH2 has a very low density, making its storage tanks physically larger, increasing the size of other components. Liquid oxygen and RP-1 typically provide a lower I_{sp} than LOX/LH2, but have some advantages. RP-1 is highly refined petroleum, similar to kerosene or jet fuel. It is stable at room temperature and is storable. Furthermore, RP-1 is much more dense than LH2, making its storage tank significantly smaller. Nitrogen tetroxide and UDMH has a lower I_{sp} than LOX/RP-1, but has the advantage that both propellants are liquid at or near room temperature, requiring little or no insulation and making them both storable for longer periods of time. Most importantly, N2O4/UDMH is *hypergolic*, meaning that the two propellants react immediately upon contact, thus not requiring a spark to initiate combustion. This makes them extremely reliable and simple to use. However, N2O4 is an extremely strong oxidizer and UDMH is a carcinogen, making both dangerous and deadly in small quantities. (Bruhn, Orlando et al. 1967; Humble, Henry et al. 1995; Sutton and Biblarz 2001)

Solid propellants combine fuel and oxidizer, holding it together with a binder. Catalysts and other compounds may also be present. There are a large variety of fuels, oxidizers, and binders, and they can be combined in a wide variety of ratios in the grain. A variety of propellants and binders are listed in Table 3, in no particular order.

The Space Shuttle Solid Rocket Motors (SSSRM's), for example, use a solid propellant that is approximately 16% aluminum fuel, 70% ammonium perchlorate (AP) oxidizer, and about 14% polybutadiene acrylonitrile (PBAN) binder, though hydroxy-terminated polybutadiene (HTPB) binder is currently most common. (Humble, Henry et al. 1995) This particular solid formulation is used in this research.

Table 3: Solid rocket propellants and binders (Humble, Henry et al. 1995)

Fuels	Oxidizers	Binders
Zirconium	Ammonium Perchlorate	Polysulfide
Titanium	Ammonium Nitrate	Polyether Polyurethane
Magnesium	Sodium Nitrate	Polybutadiene Acrylic Acid
Aluminum	Potassium Perchlorate	Polybutadiene Acrylonitrile
Aluminum Hydride	Potassium Nitrate	Nitrocellulose
Beryllium	Nitronium Perchlorate	Carboxy-terminated Polybutadiene
Boron		Hydroxy-terminated Polybutadiene
Beryllium Hydride		Nitrate Ester Polyether
		Glycidal Azide Polymer

Solid propellants can be extremely stable and can be stored for long periods of time. They can also provide immense levels of thrust relative to motor weight and are often used early during launch as boosters. The thrust profile must be designed into the solid grain geometry. Different cross sectional shapes and configurations help control propellant burn rate, altering thrust as necessary across the launch.

2.2.2 Fundamentals of Rocket Structural Materials

There are several different materials used in rocket structures. The specific material depends on the application, but there are several common materials. Major structures are primarily made out of metals due to their affordability, manufacturability, good mechanical properties at a wide range of temperatures, and relatively high strength to weight ratio. Carbon fiber composites are also being used with increased regularity.

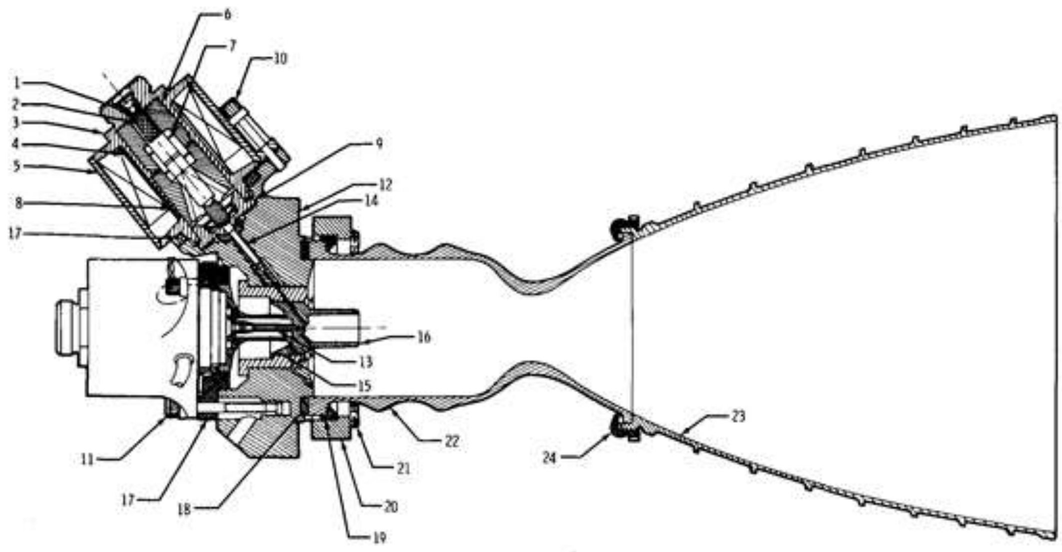
Table 4 lists some materials used in rocket structures and some of their typical applications. Some more exotic materials, such as iridium and rhenium, are used in small quantities in components like engines (Humble, Henry et al. 1995), but the application of such materials is beyond the scope of this work. A variety of other materials can be used in onboard electronics and other minor components. It is generally assumed that these occur is sufficiently small quantities when compared to other structures, and especially when compared to the gross mass of the rocket.

Table 4: Materials used in rockets and typical applications (Bruhn et al. 1967)(Humble et al. 2005)(Sutton and Biblarz 2001)(Taeber and Weary 1973)

Material	Propellant Tanks	Inter-sTages and Inter-tanks	Thrust Structure	Payload Fairing & Nose Cones	Insulation	Heat Shielding	Engines & Engine Parts	Propellant Feed Lines	Gimbal	RCS Engines	Motor Case	Motor Nozzle	Secondary Structures
Aluminum	X	X		X									X
Beryllium		X		X									
Beryllium-Aluminum		X		X									
Copper							X			X			X
Iridium							X						
Magnesium													X
Molybdenum										X			
Nickel		X					X						
Niobium							X			X			
Steel		X	X				X		X		X		X
Stainless Steel	X	X					X	X		X			
Titanium	X						X				X		
Carbon-Carbon						X						X	
CFRP		X		X							X		
EPDM					X								
GFRP*											X		
Glass/Ceramic Foam						X							
Natural Butadiene Rubber					X								
Polyurethane Foam					X								

* Glass Fiber Reinforced Polymer, not to be confused with Graphite Fiber Reinforced Polymers grouped with CFRP's

This list describes the general application of materials. Components tend to use a large variety of different materials. An example can be seen in Figure 3 where a cutaway of the RCS thruster used by the Apollo Command Module is shown. The different materials used for each component are also listed.



No.	Equipment	Description	No.	Equipment	Description
1	Trim orifice	CRES 304	13	Oxidizer preigniter tube	CRES A286
2	Strainer	CRES 316, 321, 347	14	Fuel preigniter tube	CRES A286
3	Valve body	CRES 446, MIL-E-21562, type MIL-EN6A weld rod	15	Preigniter insert	CRES A286
			16	Preigniter chamber	
4	Automatic coil		17	Thermal insulator	Plastic laminate
5	Direct coil		18	Seal	L605 cobalt-base alloy
6	Plug	CRES 446	19	Split ring	Rene 41
7	Spring	Inconel X	20	Attach ring	Rene 41
8	Armature	CRES 446 with Stellite tip	21	Attach bolts	Rene 41
9	Valve seat assembly	AM 355 with Teflon TFE seal	22	Combustion chamber	Unalloyed molybdenum, disilicide coated
10	Fuel valve attach bolts	6AL-4V titanium			
11	Oxidizer valve attach bolts	CRES A286	23	Nozzle skirt	L605 cobalt-base alloy
12	Injector housing	6061T6 aluminum	24	Nozzle attach nut	WASPALOY

Figure 3: Apollo Command Module RCS thruster cross section with component and material callouts (Taeber and Weary 1973)

It is beyond the scope of this research to go into such detail. This RCS engine alone uses over a dozen different materials. Material selection is generalized for each component to bring insight into its impacts, without overcomplicating the analysis.

2.3 Life Cycle Assessments

2.3.1 <u>Overview of LCA</u>

Environmental *life cycle assessments* (LCA's) are a means for assessing the environmental performance of a product or system. However, LCA is not a means to determine absolute environmental impacts of those systems. No environmental model can absolutely represent a system because the scale and complexity associated with building and executing those models makes verification and validation difficult, if not impossible. (Oreskes, Shrader-Frechette et al. 1994) Nevertheless, such models can be useful for providing insight into the system, so long as the proper context is understood and all of the assumptions leading to the resulting conclusions are made clear. When comparing multiple systems, LCA becomes a powerful tool because the *relative* environmental performance of those systems can be useful information when determining the environmentally preferable alternative (Goedkoop, De Schryver et al. 2010). Determining which of two systems (modeled and assessed under the same assumptions) is environmentally preferable can be done with more confidence than trying to determine whether one system, modeled without a baseline, has acceptable environmental performance.

The leading standards used for performing LCA's are ISO 14040 and 14044. ISO 14040 outlines general principles and framework, while ISO 14044 provides requirements and guidelines. A major issue with these standards is that the language is vague, and it can be difficult to determine if an LCA is being performed according to the standard. Furthermore, there is no way to certify that an LCA was performed according ISO standards. Nevertheless, ISO 14040 and 14044 do provide a useful guideline for performing an LCA. The tool used to perform the LCA in this research (SimaPro 7.3) allows for the model being built to follow the ISO standards closely, but it cannot guarantee that ISO standards were followed. (Goedkoop, De Schryver et al. 2010) Some deliberate deviations from ISO are taken in this research. These deviations are discussed and justified further in Chapter 3.

Though LCA can have many advantages, there are a number of unresolved issues. (Reap, Roman et al. 2008; Reap, Roman et al. 2008) Key problems that are most likely to influence this research include issues with data quality, allocation of environmental burdens, and system boundaries. These issues are somewhat mitigated because this research performs a series of LCA's under the same assumptions and conditions. Issues with data quality, allocation, and system boundaries affect all of the analyzed rockets equally. Though the absolute environmental impacts of these systems may not be achieved with high accuracy, the results are determined with high precision, which is necessary for determining the trends and relationships that are required to answer the research questions

2.3.2 Life Cycle Assessments of Rockets

Only two *environmental* LCA's of rockets were found in the literature. These assessments were on two military rockets, the PATRIOT Advanced Capability-3 (PAC-3 Environmental Assessment Team) rocket and the Multiple Launch Rocket System (MLRS) rocket. Neither report claimed to conform to the commonly used ISO 14040 standard for performing an LCA.

In a thorough investigation (PAC-3 Environmental Assessment Team 1997), United States Army Space and Strategic Defense Command (USASSDC) assessed the impact of PAC-3 operations on twelve environmental systems. Primary motivation for the assessment was regulatory compliance for domestic testing and firing of the PAC-3 rocket. The investigation concluded that there was no significant environmental impact of domestic PAC-3 operations.

A similar investigation (Hubbard and Ward 1998) of the MLRS was performed by the United States Army Aviation and Missile Command (AMCOM). Motivation for the investigation was primarily regulatory compliance, as with the PAC-3. The report investigated the environmental impact of constructing, testing, and deploying MLRS systems and compared then current rockets to proposed improved systems. As with the PAC-3, no significant impact on the environment was found.

Neither rocket is an orbital launch platform. Both rockets use a single stage of solid propellants to launch a payload on a ballistic trajectory within the atmosphere. This makes both highly uncharacteristic of most orbital launch platforms which typically use multiple stages that include both solid and liquid propellants. Therefore, these LCA's do not provide much useful insight into the system of interest.

2.4 Environmental Burdens of Materials

2.4.1 Upstream Burdens

It is important to understand upstream environmental burdens of materials used in rocket structures. In other vehicles, light-weighting with carbon fiber composites tends to increase the upstream impacts of the system. (Zhang, Yamauchi et al. 2011) Rockets use a variety of different and more exotic materials in their structures, bringing additional uncertainty about whether light-weighting is addressing a structures issue or a propellants issue with the environment.

The environmental burdens of the materials listed in Table 4 vary greatly. Not only can there be differences from one material to another, but different alloys or compositions of the same material can have different environmental burdens. Figure 4 and Figure 5 show the embodied energy (upstream energy required for material production) and carbon dioxide during primary production for some common materials from Table 4, expanding on some to show different alloys and compositions.

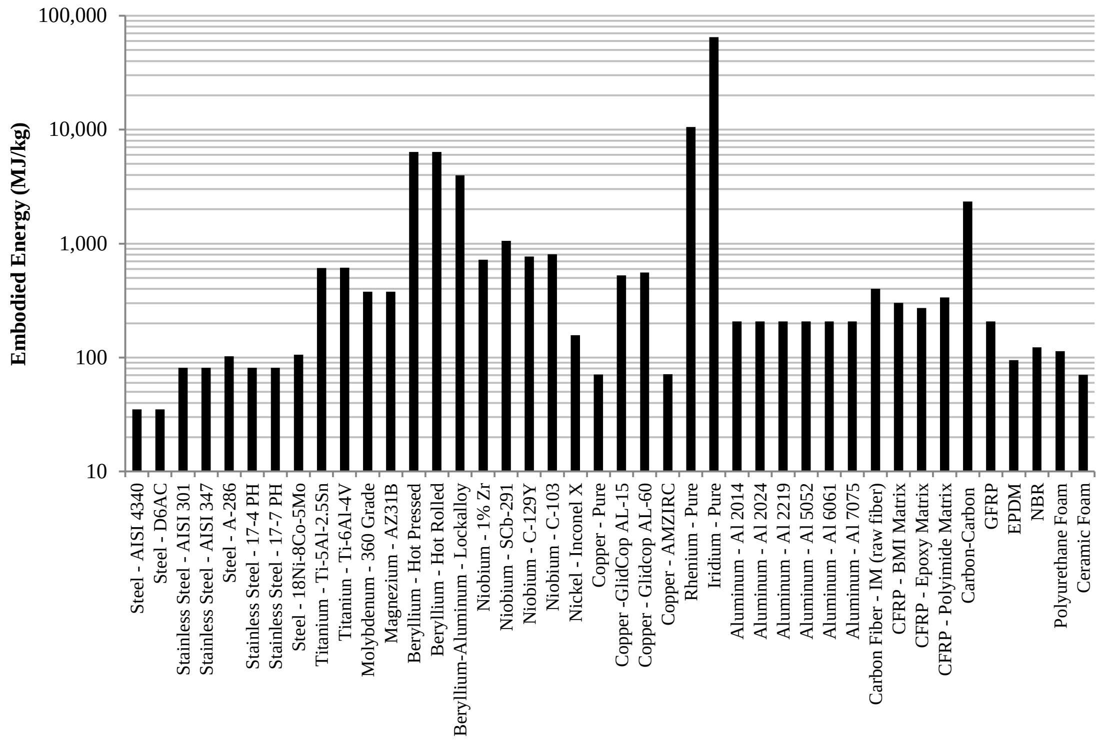


Figure 4: Embodied energy of different materials used in rocket structures (Granta 2012)

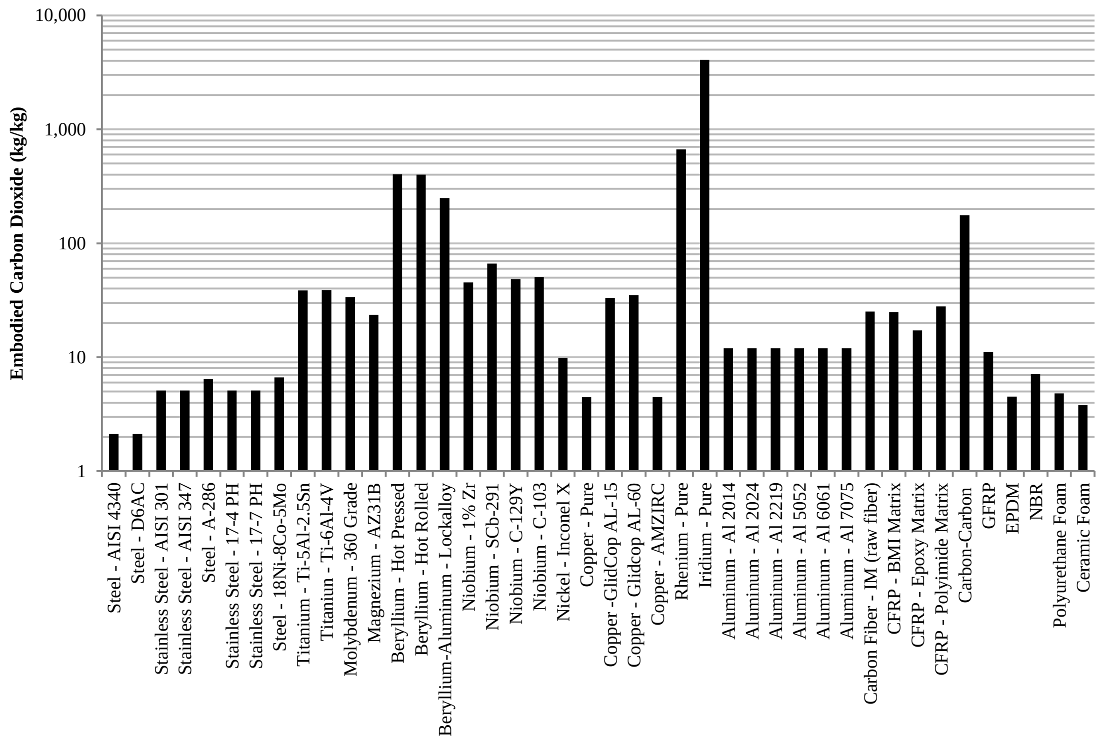


Figure 5: Embodied carbon dioxide of different materials used in rocket structures (Granta 2012)

As it can be seen, some materials require orders of magnitude more energy and produce orders of magnitude more carbon dioxide during primary production. Automobiles and airplanes tend to use a lot of aluminum, steel, and carbon fiber composites, which have relatively low embodied burdens, limiting the environmental impact of the structure of the vehicle. Rockets can use some materials like titanium and beryllium that can greatly increase the impacts of the structure, which can perhaps mitigate the environmental benefits of light-weighting to reduce propellant load.

Metals, which make up the majority of the rocket's structure, have been used for thousands of years. As a result, metal-working technology has matured and is quite advanced. Carbon fibers, though discovered as recently as the 1890's, have only been in practical use since approximately the 1960's. (Sittig 1980) Carbon fiber technology is constantly evolving, which has led to some uncertainty about the fiber's environmental impacts.

Carbon fiber composites can have much higher upstream environmental burden than that of the metals they are replacing. A composite structure using an epoxy matrix material can have an embodied energy of around 234 MJ/kg (Suzuki and Takahashi 2005), higher than the approximately 200 MJ/kg of aluminum and much higher than the 40 MJ/kg of low alloy steel (Granta 2012).

Though there may be some uncertainty with metal's burdens, it is assumed that available data is relatively accurate due to the widespread use of many metals. It is more important to reconcile any uncertainty about carbon fibers' embodied burdens because they are used so prominently in light-weighting. Furthermore, it is expected that upstream burdens increase when metals like aluminum and steel are replaced with carbon fiber composites. This has an off-setting effect on the lifetime impacts, so it is important to try to narrow the likely upstream burdens associated with carbon fibers as tightly as possible. Issues uncovered in the literature with regard to uncertainty about carbon fiber embodied burdens are discussed in Section 2.7.

2.4.2 Environmental Impacts of Rocket Structures

Environmental impacts of rocket structures, not including the payload or propellants, have not been significantly studied in literature. Due to their much lower total mass when compared to propellants, and the use of common materials and manufacturing techniques, structures are assumed to have a small environmental impact and do not gain a lot of attention.

Attention is paid in literature to rocket structures with some specific materials, though. In particular, the use of beryllium in rockets is studied closely. Beryllium has the highest structural efficiency of metals (Bruhn, Orlando et al. 1967), making it extremely desirable during light-weighting as an alternative in applications where carbon fibers may not be well suited. Though possessing some attractive properties, beryllium is seldom used in rocket structures due to its health risks. It is a carcinogen and is toxic to both humans and animals.

2.5 Environmental Burdens of Propellants

2.5.1 Upstream Burdens

There was no literature found that addresses upstream environmental burdens of propellant production. Though some of the propellants used, like LOX and LH2, have other common uses and thus have been investigated to some extent, some propellants's upstream burdens are completely ignored.

2.5.2 Use Phase Impacts of Propellants

Propellants consumed by rockets during launch are the primary focus of most of the literature that investigates environmental impacts of rockets. A rocket's use phase is fairly homogeneous, with virtually no resources being consumed from the environment and clear, visible emissions being produced by consumption of propellants. Focus on propellants is supported by the fact that the majority of a rocket's mass at launch, approximately 80-90%, are propellants. Furthermore, certain propellants, like solid propellants, are known to produce environmentally harmful combustion products. The potential environmental danger of propellants is emphasized by multiple articles

(NASA/Ames Research Center 2003; Seitzen Jr. 2005; Air Force Office of Scientific Research 2009; Moseman 2009) where the need for a more environmentally benign solid rocket propellant is discussed.

No single piece of literature was found to investigate the complete cradle to grave impacts of a propellant. Propellants have been investigated, however, at almost every stage of their life by a variety of individual pieces of literature. Though literature does focus more heavily on solid propellants, environmental impacts of liquid propellants are studied as well.

Liquid hydrogen (LH2) is a common rocket fuel and produces only steam when burned with liquid oxygen (LOX) oxidizer. Though its use phase environmental burdens would be relatively small due to its relatively benign emissions, it was recognized that production of LH2 can have significant environmental impacts. NASA investigated (Busacca 1984) the possibility of constructing a polygeneration plant near one of their launch sites for the purpose of reducing costs and overhead. The polygenertation plant would be primarily responsible for production of LH2 as a propellant, but would also produce gaseous nitrogen, sulfuric acid, and electrical and thermal energy. The environmental concern stemmed from how the hydrogen was being produced. Then current methods used steam reforming of natural gas; whereas, the polygeneration plant would produce LH2 from coal. Using coal as a feedstock for LH2 raised concerns about sulfur dioxide (SO_2) emissions that could contribute to acid rain, as well as some of the solid wastes produced when handling and processing coal. These issues were mitigated, according to the report, with innovative engineering solutions and careful treatment of byproducts.

Literature about environmental impacts of producing other propellants was not found. The *processes* for producing other propellants are well documented, but environmental considerations are not discussed. It can be seen from the description of the production processes for many propellants that a number of environmental impacts can be expected. This is primarily as a result of the potential byproducts of the various chemical reactions used in producing these propellants.

After the first twenty four Space Shuttle launches (roughly five years of operations), NASA performed a study (Hinkle and Knott III 1985) to determine the environmental impacts launches had on the local environment. The study focused on acidification of local land and bodies of water. Acidification was found to be the result of hydrochloric acid (HCl) deposition. Hydrochloric acid is a byproduct of burning the solid propellant used in the Space Shuttle Program, and was deposited in local ecosystems as it precipitated out of exhaust plumes or mixed with water used in sound damping. Aluminum (III) oxide (Al_2O_3), also a product of solid propellant consumption, was found to be deposited in local areas. Environmental impacts were documented, though long term studies on the effect on local wildlife were ongoing as of the publication of the report.

There is tremendous effort in literature to study the effects propellant combustion products have on the atmosphere. The release of HCl in the atmosphere has been identified by multiple sources (Brady, Martin et al. 1997; Ross, Toohey et al. 2000; Popp, Ridley et al. 2002) to deplete and destroy atmospheric ozone. In addition to HCl, nitric oxide (NO) (Ross, Danilin et al. 2004) and number of other reactive products released during launch (Ross, Toohey et al. 2009) have also been identified in literature to be responsible for ozone depletion. Ozone depletion at current launch levels is found to be temporary and localized to the area very near the rocket's flight path. Increased launch volume has the potential to have greater, longer term impacts on ozone depletion.

There are propellant related environmental impacts after a rocket's use phase. During launch, spent rocket stages are shed to reduce overall mass. Lower stages fall back to earth and land in downrange impact zones, effectively being landfilled. In many cases, the propellants have not completely been depleted and these stages can contain several kilograms of unconsumed propellants. Unsymmetrical dimethylhydrazine (UDMH) is a common rocket fuel, is often combusted with nitrogen tetroxide (N_2O_4) oxidizer, and is used in rockets launched from sites in Kazakhstan. The fuel UDMH itself is a carcinogen and is extremely toxic. Nitrogen tetroxide is a very strong oxidizing agent and is lethal if inhaled. Both are responsible for destruction of plant life and both domestic animal life and wildlife in downrange impacts zones.(Kuzin 1997; Carlsen, Kenesova et al. 2007; Carlsen, Kenessov et al. 2008)

Looking at unintended disposal of rockets, one report (Hines, von Hippel et al. 2002) discussed local environmental effects of perchlorate, a product also found in solid rocket propellants. The report focused on perchlorate released into the water local to the launch pad as a result of aborted or failed launches. Impacts on the environment due to rocket failure are similar to those of successful rocket launch. The key differences are that failure can lead to higher concentrations of particular burdens in locations that may or may not be localized around the launch pad.

An early report (Naqvi and Latif 1974) performed by Alcorn State University, on behalf of NASA, studied how rocket propellant waste impacts vegetation. The study focused on ammonium perchlorate (Donnet and Bansal), a component of solid rocket fuel, and its biodegradation in soil. Ammonium perchlorate is an oxidizer used in solid propellants, its presence in the environment would be the result of incomplete combustion during use or motor failure. It was found that AP significantly reduced soil's ability to grow vegetation.

2.6 Environmental Benefits of Light-Weighting

An automobile's use phase dominates its life cycle in terms of both energy consumption (Van Acker, Verpoest et al. 2009) and carbon dioxide emissions (Zhang, Yamauchi et al. 2011). The same can be said for busses and light trucks. Most of the environmental burdens during the use phase are a result of consuming fuel to satisfy energy requirement. It is therefore assumed that improved fuel economy is indicative or reduced energy consumption and decreased environmental burdens.

A correlation between automobile mass and fuel economy is identified in the literature (Das 2011; Duflou, Sutherland et al. 2012). Light-weighting is identified in literature (Suzuki and Takahashi undated) as necessary in improving fuel efficiency of automobiles. According to one study (Suzuki, Odai et al. undated) lightening an automobile by approximately 35-40% reduced energy consumption by 17-25%. Another study (Zhang, Yamauchi et al. 2011) confirmed that a 30% weight savings in an automobile reduced lifetime carbon dioxide emissions by 16%.

Light-weighting is typically done by substituting metals with CFRP's in various structures, like the vehicle's body and chassis. It is known that raw material harvesting and production of CFRP's is much higher than steel and can be higher than aluminum, depending on the particular composite structure used (Granta 2012). Upstream environmental burdens are noticeably increased with CFRP light-weighting of metal structures. Manufacturing energy and carbon dioxide burdens decrease, though only slightly, with CFRP light-weighting, and end-of-life burdens remain almost unchanged. Nevertheless, increased burdens during upstream phases are greatly overshadowed by use phase benefits.

Like automobiles, airplanes have been shown to benefit environmentally from light-weighting. Civil and commercial aircraft's lifetime environmental burdens are overwhelmingly dominated by their use phase (Ashby 2005; Ashby, Shercliff et al. 2007). As with automobiles, substituting metal structures with CFRP's in airplanes increases upstream environmental burdens. However, use phase benefits significantly outweigh any additional burdens caused by material substitution.(Zhang, Yamauchi et al. 2011)

Rockets are light-weighted in order to improve performance. Reducing the structural mass of a rocket allows for the payload to be increased by the same amount. Replacing traditional metal structures with lighter CFRP's for the purpose of environmental benefits has not been explored in the literature. Launch vehicle performance and optimizing payload mass dominate vehicle design and material selection.

2.7 Issues Identified in Literature Related to Carbon Fiber Production

2.7.1 Justification of Addition Focus on Carbon Fiber

In the case of some materials or processes, some uncertainty can be acceptable as data is not always perfectly representative of the system of interest. In the case of carbon fibers, deeper inspection of the data is required because of the prominent role they play in the research being performed here. The environmental cost-benefit of light-weighting with carbon fibers is of particular interest, as this is the crux of the research, so it is more important to address any uncertainty with this particular material.

Three issues, discussed in the following sections, regarding the upstream environmental burdens of carbon fibers were identified in literature. The typical tradeoff with light-weighting with carbon fiber composites is decreased environmental burdens during the use phase at the expense of increased upstream burdens. (Zhang, Yamauchi et al. 2011) In these systems, the use phase overwhelmingly dominates upstream phases, but it is unclear whether this is the case with rockets. Upstream burdens are expected to play a more significant role in rockets than for other vehicles, so these issues must be discussed and steps must be taken to address them.

The three issues found in literature are discussed in the following three sections, while steps taken to mitigate or resolve these issues are discussed in the inventory in Chapter 7.

2.7.2 Large Range of Published Values

Multiple sources quantify the environmental burdens of producing carbon fibers. Of significance, however, is that most of the reported quantities disagree. In particular, the embodied energy of carbon fiber spans a large range. Depending on the source cited, the embodied energy for carbon fibers can vary by over a factor of four and can lead to significant uncertainty in the results of a life cycle assessment. This is especially significant for systems whose environmental burdens are not dominated by the use phase. Some of the values found are shown in Table 5. As can be seen in Table 5, the values of embodied energy can vary significantly.

Table 5: Embodied energy of carbon fibers according to different sources

Source	Embodied Energy (MJ/kg)
Das (Das 2011)	459
University of Tokyo (Suzuki and Takahashi 2005)	286 (478*)
T.U. Delft (Van Acker, Verpoest et al. 2009)	186
K.U. Leuven (Van Acker, Verpoest et al. 2009)	364
CES EduPack 2012 (Granta 2012)	380-420
Harper International (Harper International 2009; Harper International 2012; Stry 2012)	82-239 (206-380**)
DeVegt (De Vegt and Haije 1997)	7.52
Carbon Fiber Production Model (Chapter 7)	225

*According to an older study
** Two value ranges are found in literature

It is important to note that none of the values given in Table 5 are assumed to be inaccurate. In fact, it is likely the values are accurate, describing the same *type* of carbon fiber but with different production process parameters. Type II carbon fibers, corresponding to high strength (HS) or intermediate modulus (IM) produced from polyacrylonitrile (PAN) precursors are the most likely fibers being referenced by the literature.

2.7.3 Data Richness and Diversity

When investigating the literature, multiple sources quantified the energy and carbon dioxide embodied in production. An issue began to emerge, showing a lack of richness in the published data. Further investigation to find alternative sources for the data showed that many instances of the published data stem from the same few sources.

Literature regularly cites the embodied energy and embodied carbon dioxide burden of producing carbon fibers. In the carbon fiber production process, a number of other environmental burdens are expected. These other burdens include H_2, N_2, CO, CH_4, CO_2, NH_3, H_2O, HCN, C_2H_4, and C_2H_6, amongst others. (Fitzer and Frohs 1990)

Literature tends to acknowledge that these environmental burdens exist, but seldom quantifies them. At best, literature tends to cite a handful of imprecise plots or graphs. Upon closer inspection of the sources of these graphs, it is found that virtually all sources cite a limited body of work performed by a handful of investigators. It was found that most of published literature depended on as few as two sources for these other environmental burdens, which leads to the second issue uncovered.

It is to be expected that independent investigators studying the same subject will reference each other's works. Such referencing of other's work is necessary for cross-validation and verification of research conclusions. Figure 6 represents a selection of the reviewed literature that deals with environmental burdens of carbon fibers and how one piece of literature references another. These references were found to be important to the conclusions of the citing work.

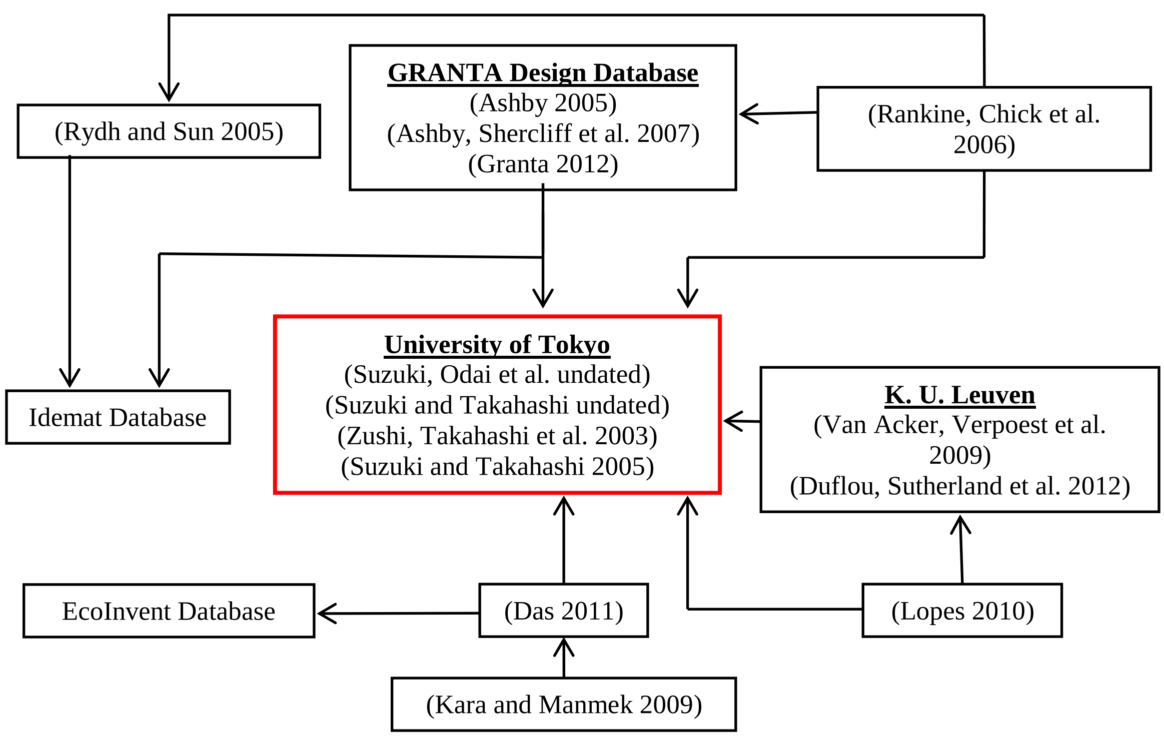


Figure 6: Representation of cross referencing of literature for information and data

It becomes evident that there are a handful of independent investigators that lead the field in terms of data and research. What becomes problematic is that those few independent investigators are the only sources of certain data. Rather than simply referring to another document to cross validate research, investigators are essentially "cut-and-pasting" data from work done by a limited group of researchers. Figure 7 shows literature that goes beyond cross referencing but relies heavily on a limited number of sources. While the cross references in Figure 6 can be explained as research due diligence, those of Figure 7 cannot be overlooked. In the case of the seminal research performed by Fitzer at the Universität Karlsruhe, not only is his data frequently referenced, but the identical plots and graphs are cited and used repeatedly. The only other publically available source found with equivalent data is from J. Bromley.

There are two significant problems with this. Firstly, it is difficult to validate or verify any data from Universität Karlsruhe because only one other publication with such information was found. Secondly, the data is quite dated at over two decades old for some of the publications, and over four decades old for others. The data does not reflect any technological advances or changes in the process or materials used.

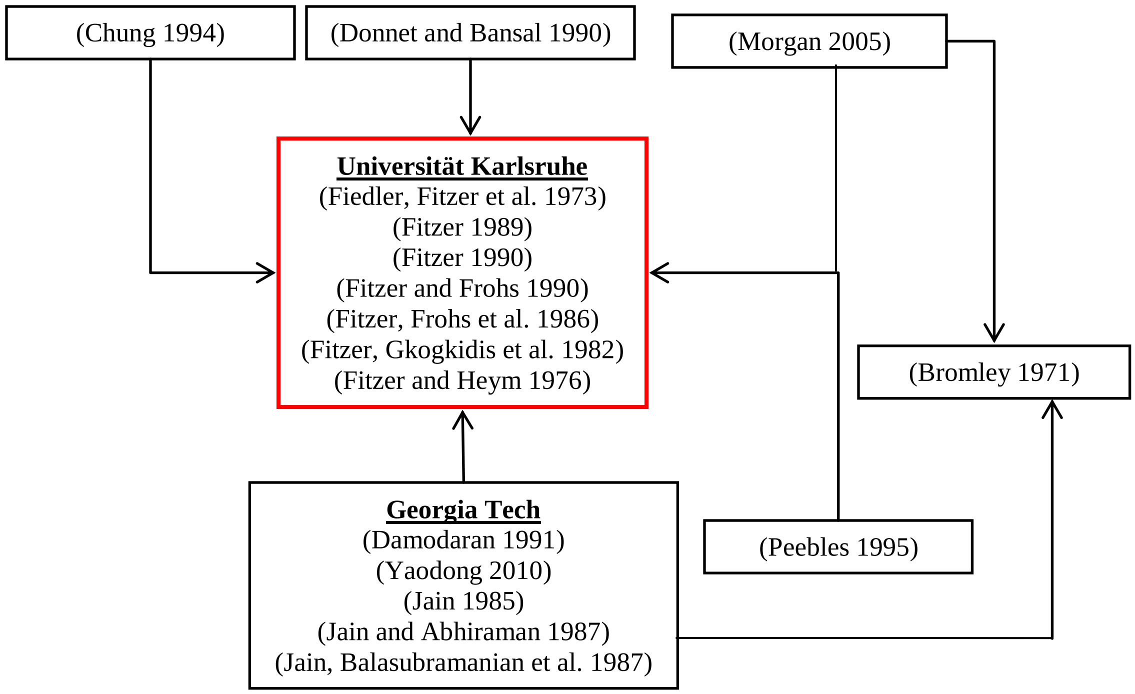


Figure 7: Representation of heavy dependence of literature on limited original sources

2.7.4 No Distinction amongst Different Carbon Fiber Types

Environmental literature makes a distinction amongst different materials during a life cycle inventory. For instance, steels are distinct from aluminum even though they are both metals. In general, literature even makes a distinction amongst different alloys of the same material, each with unique environmental burdens. The same literature, however, does not make such detailed distinctions when it comes to carbon fibers. Carbon fibers can have different mechanical properties, each made using different process parameters and possibly using different precursors. Therefore, at least some distinction amongst different types of carbon fibers and their environmental burdens must be expected.

There is evidence in literature that the environmental burdens of producing carbon fibers can change drastically, depending on the process used. It was found that production lines that produce higher volumes and with higher throughput of fiber tend to consume less energy. A 430 kg/hr fiber production line consumes as little as 207 MJ/kg of fiber, while a much smaller line with an output of fiber as low as 71 kg/hr requires as much as 380 MJ/kg.(Harper International 2009; Harper International 2012) Other process parameters like oven size and efficiency, amount of through gasses used to carry away volatiles, method for treating volatile gasses, and application of heat recovery can vary too and impact the environmental burdens.

For systems whose environmental burdens are not dominated by their use phase, under or overestimating the environmental burdens by the factors seen in Table 5 can have a significant impact on the outcome of a product's life cycle assessment, especially since embodied burdens of carbon fibers (e.g. the embodied energy) can be many times higher than those of the materials being replaced.

2.8 Chapter Summary

It can be said with a great deal of confidence that light-weighting an automobile or airplane with CFRP's has benefits to the environment. Such claims are well supported in the literature. However, the same cannot be said with such confidence about light-weighting of rockets. It is expected that light-weighting will reduce environmental impacts, but this is speculation based on experience with automobiles and airplanes. As mentioned, there are a number of complicating factors that differentiate a rocket's properties and behavior from other systems that have been assessed with light-weighting.

While investigating literature related to environmental impacts of rocket systems, very little was found that addressed the entire life cycle of the rocket. Of the life cycle assessments performed on rockets, the analysis was very focused and specific to the particular rocket being assessed. No general life cycle assessments were found. What was found was scattered research into the environmental impacts of certain components of the rocket. By far the most research that has been and is currently being conducted is on the use phase impacts of burning certain rocket propellants. While this particular aspect is being thoroughly studied, it is not being put in the context of a rocket's entire lifetime impacts. Literature looking into a rocket's impacts is scattered and very specific. What is needed is a more generalized, holistic assessment of rocket's that is detailed but still provides insight into a wide range of rockets.

No literature was found that relates the lifetime environmental impacts of a rocket to light-weighting. While this type of research is quite common for other systems, it is completely absent for rockets. The leading assumption in literature is that light-weighting simply allows an increase in payload mass. There is no discussion how the environmental impacts of launching 1 kg of payload to orbit change as the result of light-weighting.

Issues were also identified with respect to the understanding of upstream environmental burdens of carbon fibers. Carbon fibers are expected to increase upstream burdens while decreasing downstream burdens. It is necessary that downstream savings are greater than increased upstream costs if the goal of light-weighting is the reduction of environmental impacts. This is not an issue in use phase dominated systems like airplanes where the downstream benefits so dramatically outweigh the upstream costs that upstream uncertainty makes no difference. However, rockets are not expected to be use phase dominated and the potential downstream savings may be limited. In this case, uncertainty in the upstream burdens of the fibers cannot be ignored and must be addressed.

3 Approach and Methodology

3.1 Overview of Chapter Contents

This chapter begins by discussing the life cycle assessment approach used to help answer the research questions. This is followed by a discussion on the merits of using a model-based approach to performing the required analyses. Next, this chapter discusses the life cycle modeling tool used, SimaPro 7.3, and the environmental impact assessment method, ReCiPe 2008, that is used to perform the primary analysis. Finally, this chapter discusses the bounds on the research scope, sources for data, and guidelines on how to deal with issues when they come up.

The purpose of this chapter is to discuss the approach taken during the course of this research while answering the research questions. Guidelines for the research are established and important assumptions are outlined. This chapter provides some rules and framework for the research being performed.

3.2 A Life Cycle Assessment Approach to Environmental Analysis

The first research question asks whether or not light-weighting a rocket with carbon fiber composites reduces environmental impacts of that rocket. In order to answer this question at least two rockets must be compared: a baseline rocket and a light-weighted version of that rocket. The first research question specifies that any environmental benefits or harms of light-weighting must be over the *lifetime* of the rocket, meaning that the entire life cycle of the rocket must be considered.

Performing an environmental *Life Cycle Assessment* (LCA) is one way to compare the environmental performance of two or more systems over their entire lifetime. According to Goedkoop, De Schryver et al. 2010), the two most important applications of LCA are:

- *Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the aim of prioritizing improvements on products or processes*
- *Comparison between products for internal or external communications*

An LCA can highlight the most significant contributors to the rocket's environmental impacts.

Looking to other systems for guidance on what to expect, impacts associated with automobiles and airplanes were shown in the Literature Review to be dominated by the consumption of fuel, indicating that improvements that reduce fuel consumption are environmentally preferable and will have the greatest impact. It is hoped that an LCA on a rocket will determine whether they behave similarly to automobiles and airplanes in this respect. Furthermore, if it is found that a rocket behaves uniquely, the LCA shall be able to determine exactly in what way the rocket system differs.

3.3 A Model-Based Approach

The second research question seeks to determine if the effects of light-weighting are affected by differences amongst rockets configurations. These differences include which propellants are being used, the number of stages, and the lift capacity of the rocket.

There are three obstacles to assessing environmental performance of different orbital launch vehicles. The first obstacle is that the scale and complexity of the rockets themselves. The second issue is the scale and complexity of the environment that the rocket is impacting. And finally, there are a limited number of real world rockets that can be sampled in any useful level of detail, making it difficult to isolate factors that influence and drive certain life cycle behaviors. A model-based approach was taken to mitigate these issues.

Rather than assessing a real world rocket, a representative model that defines and describes a generic rocket was developed. This model sizes (determines the mass of) a rocket and its fundamental components using mathematical relationships to calculate properties of the system given a small set of design parameters. This model is termed the *Parametric Rocket Sizing Model* (PRSM). The rockets sized by the model may not be perfect representations of real world systems, but are realistic approximations made with appropriate simplifications to facilitate analysis. This model is described in detail in Chapter 4 (beginning on page 64).

A model-based approach is also taken to performing an environmental LCA on the rockets sized by the PRSM. The LCA model determines environmental impacts using mathematical calculations to relate inputs and outputs to the system to particular environmental effects. The impact assessment methodology used in the LCA characterizes specifically how certain inputs and outputs impact the environment. The characterizations and calculations used in this research are commonly available and widely accepted, helping ensure that the analysis being performed is understandable by and meaningful to a wide audience. The particulars of the LCA methodology taken are described in detail in Chapter 7 (beginning on page 144).

In the effort of answering both of the questions, it is critical to directly link changes in life cycle environmental impacts of a rocket to the light-weighting of that rocket. A model-based approach allows for transparent analysis and repeatable results.

All assumptions and simplifications are applied to each rocket being sized equally, helping to ensure the system is defined consistently and making sure different systems can be compared as fairly as possible. Furthermore, input parameters to either the PRSM or the LCA model can be varied and changed in a controlled manner. Any change in environmental impacts can be linked to the specific parameter changed, thus differences in the life cycle impacts of different rockets can be traced back to the original cause, allowing factors that drive differences in life cycle impacts of the rocket can be clearly and explicitly identified. If there are differences amongst the environmental impacts of two similar rockets, it can be conclusively determined if these differences are caused by light-weighting or by other factors.

3.4 Life Cycle Modeling and Assessments in SimaPro

The majority of the modeling and analysis is performed using SimaPro 7.3, a commonly available and widely used LCA software tool. SimaPro bills itself as "the world's leading LCA software chosen by industry, research institutes, and consultants in more than 80 countries," (PRe Consultants) making it a logical choice to construct a life cycle model and perform an LCA.

SimaPro uses a transparent framework for constructing LCA models of systems of interest. Using the tool, it is easy to define the parts that make up the rocket, its stages of life, and the various inputs and outputs during the rocket's life. SimaPro tabulates a detailed inventory of system inputs and outputs, determining the impact of each of these on the environment using an impact assessment method available to the analyst. The tool also tabulates the contribution of each part and process of the system, making it easy to determine which components warrant further investigation and which can be accepted as-is or can be neglected. In addition to detailed tables of raw quantitative data, SimaPro generates useful graphics, aiding in the communication of LCA results.

In this research, the PRSM determined the overall size of a rocket and the size of various key components. This information is plugged into a life cycle model in SimaPro, along with information about materials, fuels, and processes used by the system. SimaPro then calculates environmental impacts. SimaPro 7.3 can calculate these impacts using a wide range of standard impact assessment methods, including:

- ReCiPe
- Eco-indicator 99
- USEtox
- IPCC 2007
- EPD
- Impact 2002+
- SML-IA
- Traci 2
- BEES
- Ecological Footprint EDIP 2003
- Ecological scarcity 2006
- EPS 2000
- Greenhouse Gas Protocol

It is easy to select which impact assessment method is to be used for analysis without needing to alter the life cycle model of the rocket itself. This makes it easy to change between different methods to ensure that the conclusions drawn using one approach are matched when a different approach is taken. SimaPro also allows an analyst to define a custom method, should none of the standard methods be found adequate. The specific impact assessment method chosen for the primary analysis is discussed in detail in Chapter 7 (beginning on page 144) along with alternate methods used for cross validation.

It is acknowledged that the PRSM is not a perfect representation of a real world rocket system. It is understood that there is some error associated with not only the size of rocket components, but data associated with materials, fuels, and processes. In SimaPro, uncertainty bounds and distributions can be assigned to any value and an uncertainty analysis can be performed relatively easily. SimaPro uses a Monte Carlo simulation to perform an uncertainty analysis, resulting in a distribution of results. This helps determine if there are cases, hidden in the main analysis due to sizing error, that change the overall conclusions. It is important to determine the amount of error that is required to counter the conclusions drawn from the main analysis. If the amount of error required to counter the main conclusion is significantly larger than what can be realistically expected from the data and sizing procedure, then it can be said that the conclusion is valid.

Despite the advantages of SimaPro, there are several limitations that must be acknowledged here. One limitation is that it heavily favors European databases and impact assessment methods. This is not an issue if the analysis being performed is not region specific, but that is not the case in real world rocket systems. Another limitation of SimaPro is a lack of limitations. Though this may sound counter intuitive, SimaPro allows the analyst such considerable flexibility in modeling that it can be difficult to ensure that the analysis is being performed according to any particular standards or guidelines. Finally, SimaPro performs certain calculations linearly. Nonlinearities may be captured using creative modeling techniques, though solutions may not always be elegant or unimpeachable. Linear calculations may make it difficult to capture certain factors, like economies of scale.

Despite these limitations, SimaPro is a leading LCA software tool and its capabilities more than adequately meet the needs of this research. Should it be found that certain limitations of SimaPro may negatively influence the results of the LCA, the limitations shall be noted and their effect on the LCA discussed.

3.5 Impact Methodology Used

3.5.1 <u>ReCiPe 2008</u>

SimaPro is capable of implementing multiple impact assessment methodologies. The methodology used in this analysis is the ReCiPe 2008 impact assessment method, detailed in (Goedkoop, Heijungs et al. 2013). It is chosen because it is one of the most up-to-date methodologies available through SimaPro, and it addresses the major environmental issues of interest, including ozone depletion, acidification of water resources, human and ecological toxicity, greenhouse gas emissions, amongst others.

ReCiPe allows for three different perspectives:

- Individualist (I): representing undisputed impacts based on short-term interests and assuming optimistic scenarios for adaptation
- Heirarchist (H): representing the perspective taken by most policy driven analyses that look at both near term and far term
- Egalitarian (E): representing the most precautionary, long term, or worst case scenario for environmental impacts

In keeping with the worst case scenario assumption in this analysis, the Egalitarian perspective is taken.

ReCiPe also allows for two different indicator sets to represent relative environmental impact. These are the midpoint indicators and the endpoint indicators. The midpoint indicator scores the impacts in eighteen different categories, while the endpoint indicator aggregates these scores into three more general categories (human health impacts, ecosystem impacts, and resource impacts), which can be combined into a single representative score. The endpoint indicator and the single score approach is useful for determining if light-weighting has an overall environmental benefit. The midpoint indicator is more useful when determining where these impacts are being felt the most, and if there are any tradeoffs while light-weighting a rocket.

3.5.2 Impact Categories and Characterization

ReCiPe 2008 organizes impacts into different impact categories. Each impact category represents a particular part or aspect of the environment that is of interest. A category typically describes *where* or *what part* of the environment is being impacted. There are eighteen impact categories assigned to the midpoint level, and they are as follows.

- climate change
- ozone depletion
- terrestrial acidification
- freshwater eutrophication
- marine eutrophication
- human toxicity
- photochemical oxidant formation
- particulate matter formation
- terrestrial ecotoxicity
- freshwater ecotoxicity
- marine ecotoxicity
- ionizing radiation
- agricultural land occupation
- urban land occupation
- natural land transformation
- water depletion
- mineral resource depletion
- fossil fuel depletion

These can be grouped into three categories that define the endpoint indicators.

- Human Health
- Ecosystems
- Resources

The different impact categories and their corresponding midpoint and endpoint indicators are shown in Figure 8.

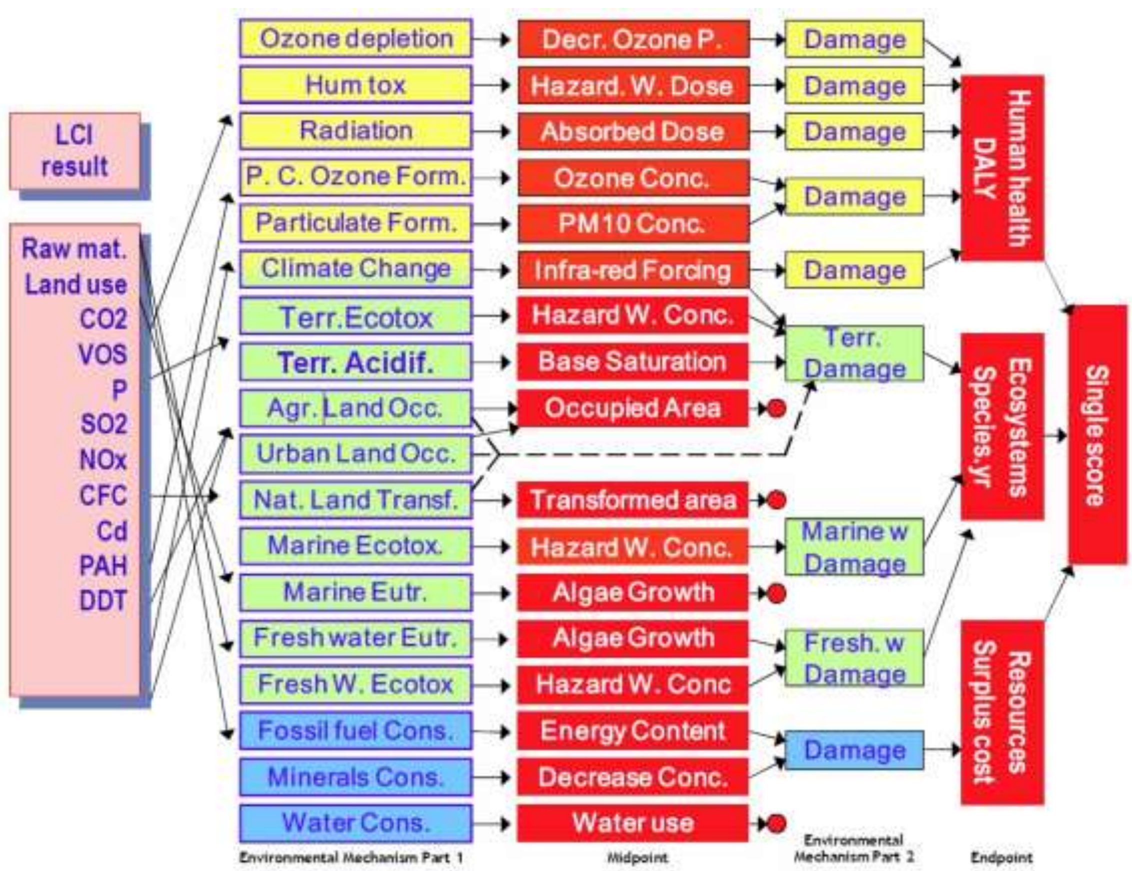


Figure 8: ReCiPe 2008 impact categories showing the midpoint and endpoint indicator sets (Goedkoop et al. 2013)

Once the LCI for the entire system is assembled, the quantitative inputs and outputs are assigned to one or more of these categories. Next, ReCiPe assigns a characterization factor to each of these inputs and outputs. The characterization factor is defined as follows, according to (Sturm undated).

> *[A characterization factor is] a factor that describes the relative harmfulness of an environmental [burden] within an environmental impact category.*

Within each category, a particular burden's characterization factor is multiplied by the amount of that burden that is released to determine the impact that burden has on the environment. The impacts are totaled across the impact category to determine the total environmental impact of that category.

Additional details about the ReCiPe 2008 impact assessment methodology, such as definitions and details about characterization factors and calculations, can be found in (Goedkoop, Heijungs et al. 2013).

3.5.3 Units

Each impact category for both the midpoint level and endpoint level has their own set of units. The units for each category are relatively descriptive as to the kind of impact that is being felt on the environment. For instance, the midpoint indicator of water depletion has units of volume, while the endpoint indicator of human health is represented in unit called the DALY, which is the sum of years of life lost and years of life disabled for a person due to being exposed to these environmental burdens. Such detail is useful in determining the specific impacts of the system, but insight is also required about the general environmental behavior of the system. Therefore, impacts are aggregated into a single score that indicates the environmental impacts of the system.

When being combined to a single score, the overall environmental impact is represented in terms of *points*. Each impact category is assigned a characterization factor, just like was assigned to each burden within each category, weighing that particular categories importance on environmental impacts. The results from this calculation are summed and the system is assigned a single score as to its environmental performance.

The singe score method provides great insight, even though it is somewhat general and subjective. The single score approach is not intended to express environmental impacts in absolute terms, but it is extremely useful when used to compare the performance of two systems. The single score method can help indicate whether light-weighting is indeed better for the environment. If a trend is identified, then further investigation of midpoint indicators can determine in exactly which way light-weighting is better.

3.6 Scope and Guidelines for Analysis

3.6.1 Types of Rockets Considered

There are virtually limitless combinations of propellants, payloads, staging options, and materials that can be used in a rocket. Though some data is available on real world rockets, this data tends to be scattered and limited. The goal of this research is to identify trends and general relationships, and accomplishing this goal would be difficult with data on relatively few actual rockets. For this reason, rockets are sized and defined according to a model.

There is a lot of freedom to model many different rocket configurations. The model is useful because parameters can be changed one at a time to determine that parameter’s influence on environmental impacts, but some limitations are necessary. In order to maintain a level of consistency, the rockets being considered are restricted to a limited number of possible propellant combinations, staging options, and payload sizes.

Several simplifying assumptions are also made to keep the analysis clear and focused. Real world data is used to fill in information that the model cannot predict and to validate results from the model.

Many different systems can be grouped under the heading of *rockets*. Analysis is limited here to orbital launch vehicles, or larger rockets capable of achieving Earth orbit. Insight into a broad range of rockets is desired and choosing to assess orbital launch rockets provides insight into smaller, suborbital rockets without narrowing the scope too restrictively.

3.6.2 System Boundary and Life Cycle Stages

The system of interest is a rocket used to launch a payload into Earth orbit. The payload is considered strictly as a mass being launched into orbit and any environmental impacts associated with its life are not allocated to the rocket. The analysis focuses on environmental impacts during material harvesting, manufacturing, and use of the rocket. During analysis, end of life burdens, though considered, were found to be small to negligible compared to these phases of life, so discussing of this phase of life is limited.

Processes during the manufacturing and use phase are modeled in a second order sense. This means that all processes, materials, and resources are considered (as best as possible) but capital goods are neglected. Materials and other resources being consumed by the rocket are modeled in a first order sense, meaning that only the production of the material or resources is considered, and other processes and capital goods are neglected.

The upstream boundary on the rocket's life cycle shall be harvesting materials for the production of structural components or propellants. The downstream boundary shall be the disposal of spent rocket stages. During the life cycle, only direct interactions between processes used or consumed by the rocket and the environment are considered. This system boundary is discussed in more detail in Section 4.2, beginning on page 64.

3.6.3 Using ISO 14040 and 14044 as a Guideline

According to the ISO 14040 and 14044 standards, an LCA is made up of four parts: goal and scope definition, inventory analysis, impact assessment, and interpretation. ISO 14040 defines the principles and framework of the LCA, while ISO 14044 provides requirements and guidelines. (Goedkoop, De Schryver et al. 2010)

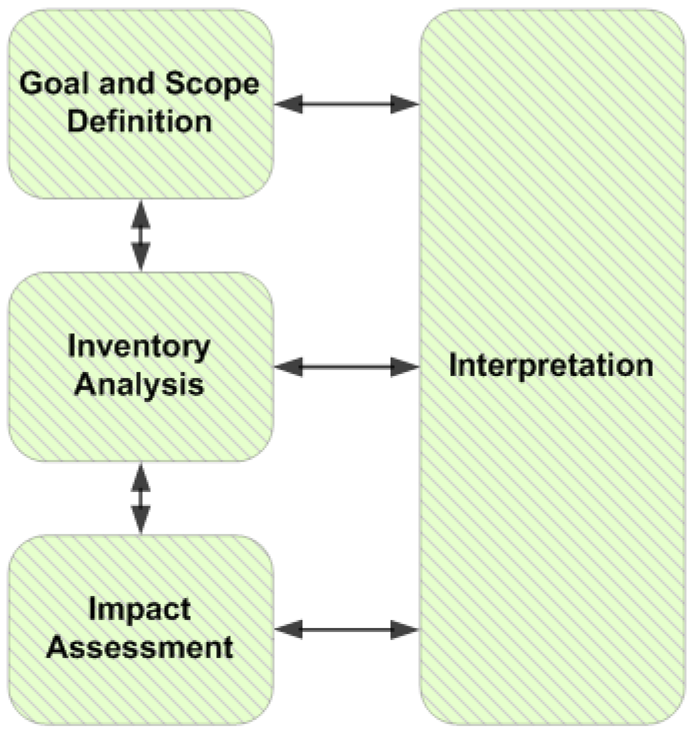


Figure 9: Parts of an LCA according to ISO 14040 and 14044

This research uses the ISO standard as a guideline, largely adhering to its specification with a few intentional deviations. Nevertheless, there is one major obstacle to applying the ISO standards and there are some intentional deviations from the standard that are taken.

There is no way of certifying or verifying that a particular LCA was done according to the ISO standards. This represents an absence of a formal set of requirements that must be satisfied to state that an LCA was done according to the standard. Therefore, it is impossible to absolutely confirm that the standard was indeed followed. Without any formal means of testing an LCA for ISO compliance, it is impossible to objectively claim that the standard was followed. At best, it can be stated that the ISO standard for LCA was followed according to the best of the analyst's (my) ability.

Two intentional deviations are taken from the ISO 14040 and 14044 standards. The first intentional deviation from the standard is the use of weighting across different impact categories, which is prohibited by the standard when making public comparisons. This analysis draws conclusions from both weighted and un-weighted impact factors, and the possibility of using weighting for future interpretation of results is not entirely ruled out. Secondly, the ISO standard requires an external, independent peer review. It is impossible to perform such a peer review at this time due to time and resource constraints. However, the possibility of a peer review following the completion of this research is possible.

3.6.4 Allocation of Processes and Life Cycle Impacts

Impacts associated with materials and processes used for the production of individual rocket components are allocated to that individual component. The use phase of the rocket, i.e.: the burning of rocket propellants, is allocated to the rocket as a whole and not to any individual component, such as the engines.

In some cases, processes can produce useful byproducts referred to as *avoided products* in SimaPro. The impacts of the process may be split between the primary products and the avoided products. In this analysis, it is assumed that all impacts are allocated to the primary products of the process or to the rocket itself and avoided products are essentially "free" of impacts. This provides a worst-case-scenario in terms of the rocket's environmental burdens, which is of more interest in this research. Furthermore, it avoids the issue of assigning and justifying different allocation percentages to different products and byproducts.

3.7 Data Sources

3.7.1 Data from Databases Used by SimaPro 7.2

SimaPro 7.2 accesses various pre-existing databases. These include (amongst others):

- EcoInvent v.2
- US LCI (United States Life Cycle Inventory)
- ELCD (European reference Life Cycle)
- US Input Output
- EU and Danish Input Output
- Swiss Input Output
- LCA Food
- Industry data v.2

These databases provide a good foundation for assembling a *Life Cycle Inventory* (LCI) for the system of interest. The LCI is an assembly of all of the inputs and outputs to a particular process or aspect of the system. Some common resources or processes have multiple entries in different databases, allowing for the selection that is most representative of a rocket's life cycle. The data may not be a perfect definition of the system, but it is the best approximation that can be expected and achieved at this time.

A large part of the LCI used in this research depends on SimaPro's built-in databases, but not all inputs have entries in these databases. In these cases, external literature must be used to assemble an inventory for the particular input.

3.7.2 External Literature

External literature can take many forms, such as academic research articles, industry reports, or government documentation. What is sought is a detailed description of the real world production of a particular resource or process, along with quantitative information as to the specific inputs and outputs to the resource or process, so that an inventory that best represents a real world rocket can be assembled.

Finding this type of detailed and accurate data can be difficult and detailed information simply may not be available for certain processes. In these cases, external literature shall be consulted to approximate the processes of interest as best as possible. Though the process may be idealized or substantially simplified from what can be found in the real world, these approximations (at least) help point the analysis in the correct direction. As mentioned earlier, SimaPro is capable of including uncertainty in its analysis to help account for any error due to approximations.

3.7.3 Dealing with Data Uncertainty

Poor data quality and data uncertainty are a leading issue in LCA. (Reap, Roman et al. 2008) Especially in systems as large and complex as a rocket, it can be prohibitively difficult to obtain accurate data. Therefore, it must be accepted that issues diminishing the accuracy of the analysis and increasing uncertainty about results shall be encountered. Steps can be taken to mitigate these issues, though.

SimaPro can be used to perform an uncertainty analysis on certain parameters. While assembling the LCI, entries or inventories that are suspected of poorly representing the system can be assigned some amount of uncertainty. Uncertainty is tolerable if it does not change the conclusions of the analysis. The way in which and the amount of uncertainty assigned to certain values is discussed in detail in Chapter 10.

3.8 Simplifying Assumptions

The complexity of the system of interest and the very nature of environmental modeling requires that simplifying assumptions be made to facilitate analysis. According to George E. P. Box, “Essentially, all models are wrong, but some are useful.”(Box and Draper 1987) The biggest assumption being made in this research is that properties of the system of interest (i.e.: the rocket) can be approximated using a mathematical sizing model, and its life cycle impacts on the environment can be represented with a life cycle model. Though these models may not accurately determine the life cycle environmental impacts of a real world rocket, the results are precise, repeatable, and do provide useful insight into the performance of the system.

Specific simplifying assumptions are made throughout this analysis. These assumptions are identified and discussed as they become relevant.

3.9 Adoption of a Worst-Case Scenario for Analysis

When questions arise as to the amount of a particular burden, the allocation of a particular burden, or assumptions that can lead to changes in the results in the LCA, a worst-case scenario is adopted to serve as a guide. A worst-case scenario is useful because it bounds the potential impacts of a rocket between nothing (no impacts) and the results of the analysis. With such an approach, it can be more reliably said that the environmental impacts of a particular rocket do not exceed a certain amount. This is important because, as shown in the Literature Review, environmental impacts of rockets are generally considered to be negligible in the bigger picture of mankind's interaction with the environment across the globe. If after a worst-case scenario assessment it is found that rockets still contribute negligibly, then specific reasons to reduce environmental impacts, beyond simply seeking a healthier global environment, shall be necessary.

3.10 Chapter Summary

This chapter began by describing and justifying a model-based approach to analysis. Such an approach is useful when the real world system is inaccessible or too complicated to study directly. A model-based approach also allows for the simulation and analysis of many different scenarios while allowing variables and parameters to be changes in a controlled and predictable manner. This helps keep the results precise, consistent, and repeatable. This also helps to strongly connect changes in results directly to parameters that were altered to obtain those different results.

SimaPro 7.3 was also discussed as the life cycle assessment tool. SimaPro is a commonly used, well accepted means of performing the types of environmental assessments found in this research. The ReCiPe 2008 environmental impact assessment methodology was also identified and described. This impact methodology is current, widely used, and well accepted in both academia and industry. Life cycle analysis is performed using ISO 14040 and 14044 as a guideline, though strict adherence is not required and several intentional deviations are taken.

This chapter also discussed the sources for data and how data uncertainty is addressed by performing an uncertainty analysis. As a general rule, this research takes a worst case scenario stance on issues that may arise.

4 DESCRIPTION OF THE ROCKET SYSTEM AND SIZING

4.1 Overview of Chapter Contents

The purpose of this chapter is to describe the actual system being analyzed during the life cycle assessment. There are many different possible rocket configurations that can be assessed, so it is important to clearly define exactly which configurations are being assessed. Furthermore, it is important to clearly define every component of the rocket that is under consideration so there is less ambiguity as to how the analysis was performed and how the final conclusions were reached.

This chapter details, specifically, which propellants, payload masses, and staging options are considered. It also specifies exactly which components are assumed to make up the rocket. The majority of this chapter is devoted to the *Parametric Rocket Sizing Model* (PRSM). This model sizes (determines the mass of) individual components of the rocket. The necessity for such a model is driven by the need to analyze a wide range of different rocket configurations. It must be possible to change certain parameters in a controlled manner so that it can be positively determined if changes in environmental impacts are the result of light-weighting or of some other factor.

Having the ability to size different rockets is important because it means that many different scenarios can be assessed. The more scenarios that are assessed, the better the relationship between light-weighting with carbon fiber composites and lifetime environmental impacts of a rocket can be understood.

4.2 A Rocket's Life Cycle

There are four fundamental phases to a product's life according to ISO 14040. These are the material harvesting phase, manufacturing and assembly phase, use phase, and end of life phase. The rockets under consideration here experience all four of these phases. The life cycle for a typical rocket can be seen graphically in Figure 10. Design of the rocket, which can arguably be attributed to its life cycle, is neglected here.

The system boundary is drawn such that material harvesting and refining are not modeled in great detail. As discussed earlier, material harvesting and refining is modeled in a first order sense, where capital goods are neglected and not all of the required processes are modeled. These processes are largely represented by pre-existing database entries that contain a significant amount of data for real world processes. These database entries are found to represent processes that are quite similar to those found during rocket material harvesting, but no additional insight about a rocket's life cycle impacts are expected to be found if this phase is modeled in more detail. The downstream boundary is such that end of life scenarios is considered, but shall be modeled in a first order sense with less detail than other phases of life. This is because of the variety of possible end of life scenarios. During analysis, it was found that the end of life represented a small to negligible influence on the rocket's life cycle impacts. It was determined that no additional modeling or detail in the end of life would provide additional insight into a rocket's life cycle impacts and would not help answer the two research questions.

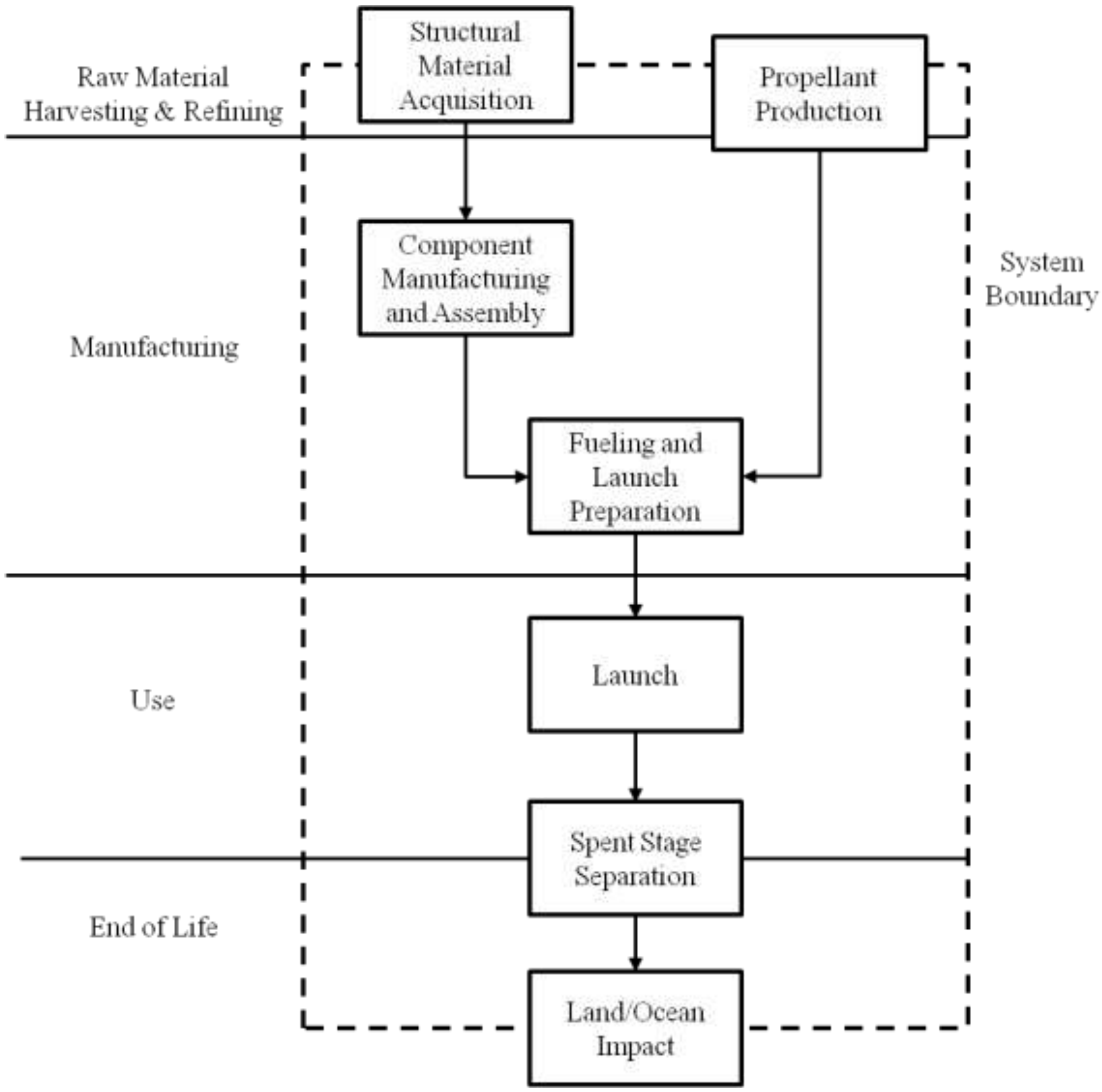


Figure 10: Typical rocket system life cycle stages

This life cycle can be simplified. Some of the events during the life cycle, like stage separation, are discrete events that mark a transition from one phase to the next, but do not themselves necessarily produce environmental burdens. Other events, such as propellant production, span multiple phases since the harvesting of resources and manufacturing of that element occur effectively at the same time. A worst-case scenario can also be assumed with environmental burdens during launch and during end of life. It is assumed that all emissions during launch occur in the atmosphere. Likewise, it is assumed that any component of the rocket that is released as space debris shall eventually fall back to Earth to be effectively landfilled or left in the ocean. The simplified rocket life cycle considered in this research is seen in Figure 11.

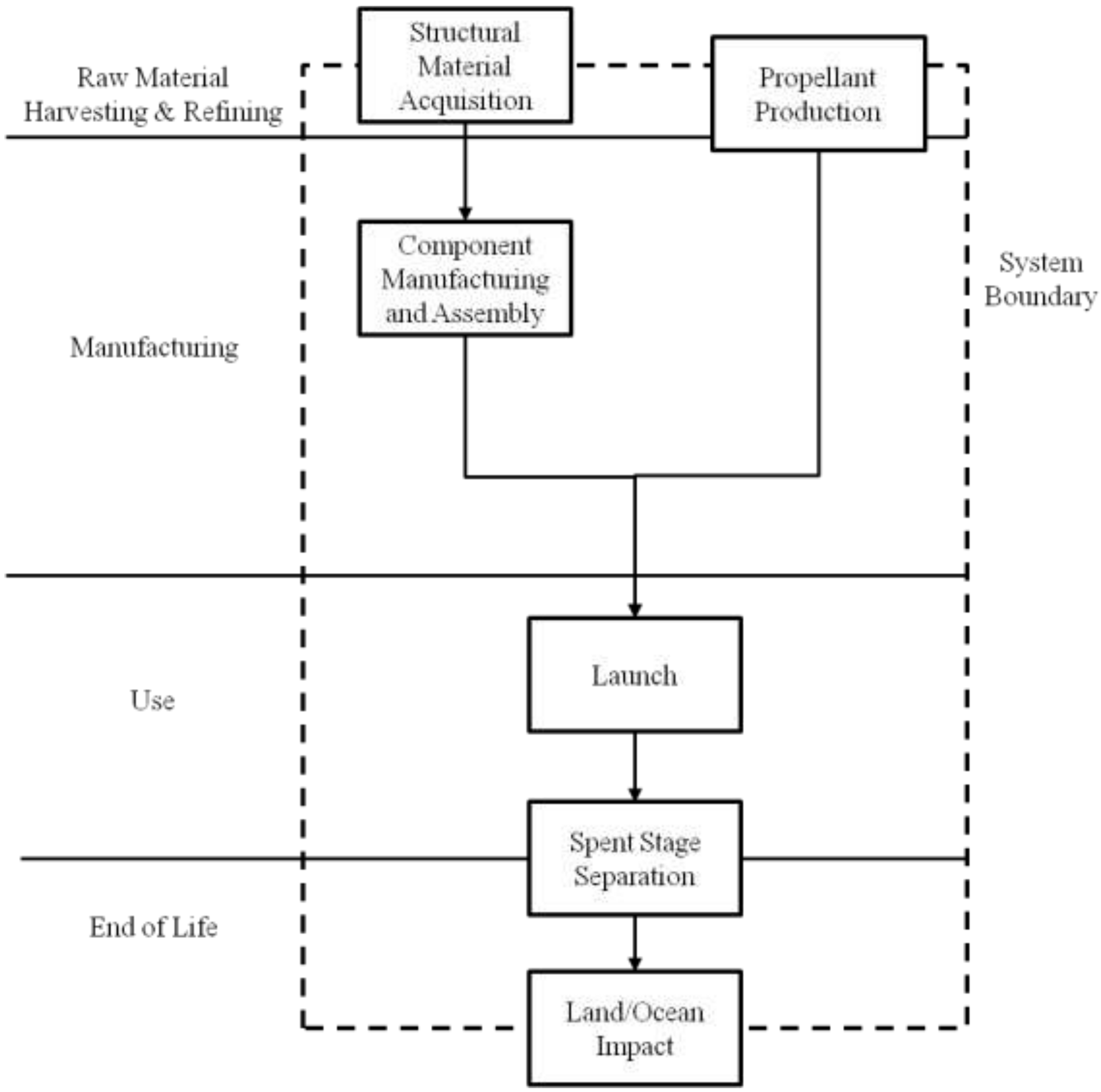


Figure 11: Simplified life cycle of a rocket used for the life cycle assessment

Resources include materials used to produce rocket structures and the rocket propellants themselves. The resources harvesting and refining phase is a cradle-to-gate process that begins with gathering the resources from nature and ends just prior to when the resource is committed in a manufacturing or assembly process that adds value specifically towards the production of a rocket. Some resources may be gathered from recycling streams of as byproducts of other processes. In keeping with the worst-case scenario assumption, unless predefined otherwise in an existing inventory database that is used, all resources are assumed to be virgin.

The manufacturing and assembly phase of life includes value-adding manufacturing processes specific to producing a rocket. This includes the fabrication of individual components and assembly of those components. At some point between the beginning of this phase and the actual launch, the rocket propellants must be added to the system. Though this is a discrete event in the assembly of the rocket, it is assumed that this particular stream in the life cycle goes directly from propellant production to launch and "fueling-up" the rocket can be neglected.

The rocket's use phase is the launch of the rocket. Rocket use and rocket launch are used interchangeably and are assumed to refer to the same phase of life. The use phase begins once the propellants are ignited and the rocket begins accelerating the payload. The use phase ends once the final stage of the rocket has burned out and the rocket has delivered the desired ΔV to a payload mass and the stage separates. Once a stage has separated from the rocket (or the payload) it is immediately considered to be in its end of life scenario. End of life begins immediately upon separation and not when the spent stage impacts the surface (either on land or in the ocean) as excess propellants can still be released into the atmosphere during descent. Since this release of excess propellants is not part of the intended function of the rocket, and since is it necessary in delivering the payload into orbit, it is assumed to be part of the end of life scenario. It is assumed that the rocket does not consume any resources from the environment around it during use. The only interaction with the environment during the use phase is the result of the motors or engines, such as the emission of combustion products as exhaust into the atmosphere.

Certain rocket components can be recovered and reused. Solid motors are often recovered and refurbished after each flight as seen with the Space Shuttle Solid Rocket Boosters (SRB) and the Graphite Epoxy Motors (GEM) used on the Delta II (The Boeing Company 2006). Some companies like SpaceX are also striving to recover liquid propellant stages of a rocket. (SpaceX 2013) Historically, though, much of a rocket's inert mass is discarded and landfilled once it is spent. These components are assumed to fall back to Earth and crash in downrange impact zones or splash zones. (Kuzin 1997) In keeping with the worst-case scenario assumption, it is assumed all of the rocket is landfilled and none of the rocket is recovered for future use. This bounds the environmental impact of the rocket by establishing a maximum.

In this analysis, it is assumed that lower stage components and the payload fairing are landfilled in a downrange terrestrial impact zone along with some portion of the excess propellants contained in the tanks. In an alternate scenario, it is assumed that the spent stages impact in the ocean, rather than on land.

4.3 Simplifying Assumptions Used in Rocket Sizing

A rocket is a complex system, and its life cycle can be equally complex. For example, the Saturn V rocket was composed of over 3 million individual parts, making up 700,000 assemblies. These parts and assemblies were supplied by over 20,000 contractor companies, involving as many as 400,000 individuals. The use phase of the rocket included a three stage burn where emissions were produced and released into multiple layers of the atmosphere. Each spent stage fell to Earth, with parts impacting across a large stretch of ocean. (Marshall History Office 2000)

Modeling the entire life cycle of such a rocket is prohibitively difficult, but insight can still be gained about the behavior of the system if simplifications are made to facilitate modeling and analysis. Three assumptions are made to simplify the rocket of interest:

- a rocket is made up of a manageable number of components
- the size of each component can be determined using mathematical relationships based on historical data
- each of these components can be approximated as being made up of a single material produced with a single generalized process, unless specified otherwise

These assumptions and sizing equations are applied equally to each rocket being sized. Though some assumptions may cause the modeled rockets to differ from real world systems, the results are good enough to provide insight into their environmental behavior of the system. Trends are still identifiable across different stages, propellant combinations, and payload masses when a rocket is light-weighted.

4.4 Description of the Rocket, Fundamental Components, and Configurations Considered

4.4.1 The Payload

It is assumed here that the payload being launched into orbit is simply a mass. Environmental impacts associated with the payload itself are allocated to its life cycle, and not the life cycle of the rocket. Therefore, there is no need to define the payload as anything more than a mass.

Eighteen different payload masses to LEO are considered. Eight of these payload masses are exclusively launched by rockets using solid propellants, eight are launched by rockets using liquid propellants, and two payload masses are assumed launched by both solid and liquid propellant rockets. The payload masses are as follows:

- 500 kg (solid only)
- 750 kg (solid only)
- 1,000 kg (solid only)
- 1,250 kg (solid only)
- 1,500 kg (solid only)
- 1,750 kg (solid only)
- 2,000 kg (solid only)
- 2,250 kg (solid only)
- 2,500 kg (solid and liquid)
- 5,000 kg (solid and liquid)
- 10,000 kg (liquid only)
- 20,000 kg (liquid only)
- 35,000 kg (liquid only)
- 50,000 kg (liquid only)
- 75,000 kg (liquid only)
- 100,000 kg (liquid only)
- 150,000 kg (liquid only)
- 200,000 kg (liquid only)

Since it is assumed that all rockets are launching their payload to LEO, with a fixed ΔV requirement of 9,000 m/s, one rocket lifting 10,000 kg is approximately comparable to two rockets lifting 5,000 kg, and so on.

4.4.2 Propellants

Rocket propellants are burned to generate thrust. There are two types of propellants considered here, liquid and solid. The liquid propellants are assumed to be a combination of an oxidizer and a fuel, stored separately until combustion. The solid propellant is assumed to have both the oxidizer and fuel pre-mixed and held together with a binder in the propellant grain.

Three common liquid propellant combinations that are representative of a large variety of different rockets used by various rocket manufacturers across the globe are assessed. The three liquid propellant combinations are:

- Liquid Oxygen – Liquid Hydrogen (LOX/LH2)
- Liquid Oxygen – Rocket Propellant 1 (LOX/RP1)
- Nitrogen Tetroxide – Unsymmetrical Dimethylhydrazine (N2O4/UDMH)

Many different solid propellant formulations exist and it is necessary to specify one particular combination of oxidizer, fuel, and binder. The solid propellant used has a formulation similar to the Space Shuttle Solid Rocket Boosters, known as the *Ammonium Perchlorate Composite Propellant* (APCP) (Humble, Henry et al. 1995):

- 16% Aluminum
- 70% Ammonium Perchlorate
- 14% PBAN

Properties associated with these propellants and their propulsion systems can be found in Table 6. These properties are necessary for sizing the rocket and shall be referenced when the sizing procedure is outlined in later sections.

Table 6: Properties of liquid propulsion system

Propellants	$\rho_{oxidizer}$ (kg/m^3)	ρ_{fuel} (kg/m^3)	O/F Ratio	$I_{sp,sl}$ (s)	$I_{sp,vac}$ (s)	$I_{sp,used}$ (s)
LOX/LH2	1,141	70.85	5.5:1	318	450	425
LOX/RP1	1,141	800	2.25:1	293	333	315
N2O4/UDMH	1,443	790	1.5:1	283	312	300
Solid	1,760		*n/a*		284	285

For simplicity here, the properties of N2O4/UDMH are assumed for the *Reaction Control System* (RCS). Though many RCS thrusters consumed monomethylhydrazine (MMH) instead if UDMH, like the thrusters used on the Space Shuttle and those used on the rockets flown during the Apollo program (Humble, Henry et al. 1995), it is assumed that the two propellants are similar enough to one another that the approximation can be made. Both UDMH and MMH have similar chemical formulae, both are hypergolic with N2O4, and both are produced using a similar process. (Powell 1968; Schmidt 1984) More detailed analysis where MMH is used in place of UDMH in the RCS thrusters can take place in future exploration of this work.

It is assumed the RCS propellants (not including residuals and reserves) are consumed during launch.

4.4.3 Inert Components

Inert components include everything on the rocket that is not the payload itself or the main propellants or RCS propellants consumed during launch. These components include structural components, protection, propulsion systems, onboard electronics and avionics, and unconsumed propellants.

Since it would be impossible to model and assess each of the millions of components that go into a rocket, it is assumed that the rocket is made up of a limited number of major components. Such a great generalization of components may not be desirable in most circumstances, but no such assessment has been performed on a rocket before, making even these generalizations far more detailed and descriptive than what is currently available in literature.

Not including the payload and propellants consumed during use, it is assumed that a rocket is an assembly of 32 possible components. These components, their function, and the primary material used in their construction are outlined in

Table 7. Components marked with an asterisk (*) are candidates for light-weighting with CFRP's.

Table 7: Inert components of a rocket assumed for analysis

Component	Function	Material
Structure		
Fuel Tank	store fuel	aluminum
Oxidizer Tank	store oxidizer	aluminum
Fore Inter-Stage Adapter*	connect current stage to next stage	aluminum
Aft Skirt*	protect aft section of the rocket	aluminum
Inter-Tank Adapter*	connect two propellant tanks	aluminum
Payload Fairing*	protect payload in the atmosphere	aluminum
Thrust Structure	connect engines to rocket	iron-based superalloy
Motor Case*	primary solid motor housing	low alloy steel
Protection		
Fuel Tank Insulation	insulate fuel tank	polyurethane foam
Oxidizer Tank Insulation	insulate oxidizer tank	polyurethane foam
Base heat Shield	protect base of rocket from engine heat	ceramic/glass foam
Motor Case Insulation	insulate motor casing from burning propellant	nitrile rubber
Propulsion		
Main Engines	primary propulsion	iron-based superalloy, aluminum, stainless steel
Main Propellant Feed Lines	feed propellants to engine	stainless steel
Gimbal	pivot engine to vector thrust	iron-based super alloy
Motor Nozzle	solid motor exhaust nozzle	graphite
Control		
RCS Engines	minor rocket turns, orientation, and positioning	cobalt, molybdenum, aluminum
RCS Oxidizer Tank	store RCS oxidizer	titanium
RCS Fuel Tank	store RCS fuel	titanium
RCS Propellant Feed Lines	feed RCS propellants to RCS engines	stainless steel
Avionics		
Guidance & Navigation	guide and navigate rocket	electronics
Communication & Tracking	communicate with ground control and track rocket	electronics
Data Processing	process rocket data	electronics
Environmental Control		
Thermal Control System	environmental control for payload	electronics
Other Non Cargo		
Motor Ingiter	ignite solid propellants	generic explosive
Ordinance	destroy rocket in case of emergency	generic explosive
Unused Propellants		
Main Propellant Residuals	excess main propellant in tanks and feed lines	(same as main propellants)
Main Propellant Reserves	excess main propellant	(same as main propellants)
Main Propellant Pressurant	maintain main propellant tank pressure	helium
RCS Propellant Residuals	excess RCS propellant in tanks and feed lines	(same as RCS propellants)
RCS Propellant Reserves	excess RCS propellant	(same as RCS propellants)
RCS Propellant Pressurant	maintain RCS propellant tank pressure	helium

It was noted earlier that each component is assumed to be made of a single material, while three materials are found listed for the main engines and the RCS engines. These two components were found to be sufficiently large enough, complex enough, and requiring materials with high embodied burdens that it would be better to model them as an assembly of multiple materials. Based on literature (Pratt & Whitney 1966; Taeber and

Weary 1973), these components are assumed to be made up by equal thirds of three different materials.

Determining which components are used and how many variations of each component are found on each rocket depend on the number of stages. The following section details the staging options that are considered in this analysis.

4.4.4 Number of Stages Considered

Three staging options are considered:

- Two Stage (liquid only)
- Three Stage (liquid only)
- Four Stage (solid only)

For the two and three stage liquid propellant rockets, it is assumed that the same propellant combination is used across all stages of the rocket. Similarly, it is assumed the same solid propellant combination is used in all stages of the four stage rocket. The properties of each propellant, found in Table 6 (found on page 73) are assumed constant across each stage.

Each stage does not include every inert component. The components included for each rocket by stage are given in Table 8, Table 9, and Table 10. Note, that different stages can use varying sizes of the same component.

Table 8: Inert components included in each stage for a two stage liquid bipropellant rocket

Stage 1	Stage 2
Oxidizer Tank	Oxidizer Tank
Fuel Tank	Fuel Tank
Fore Inter-Stage Adapter	Fore Inter-Stage Adapter
Aft Skirt	Inter-Tank Adapter
Inter-Tank Adapter	Thrust Structure
Thrust Structure	Payload Fairing
Oxidizer Tank Insulation*	Oxidizer Tank Insulation*
Fuel Tank Insulation*	Fuel Tank Insulation*
Base Heat Shield	Base Heat Shield
Main Engines	Main Engines
Propellant Feed Lines	Propellant Feed Lines
Gimbal	Gimbal
Main Propellant Residuals	RCS Engines
Main Propellant Reserves	RCS Oxidizer Tank
Main Propellant Pressurant	RCS Fuel Tank
	RCS Propellant Feed Lines
	Guidance & Navigation
	Communication & Tracking
	Data Processing
	Thermal Control System
	Ordinance
	Main Propellant Residuals
	Main Propellant Reserves
	Main Propellant Pressurant
	RCS Propellant
	RCS Residuals
	RCS Reserves
	RCS Pressurant

* Cryogenic propellants only

Table 9: Inert components included in each stage for a three stage liquid bipropellant rocket

Stage 1	Stage 2	Stage 3
Oxidizer Tank	Oxidizer Tank	Oxidizer Tank
Fuel Tank	Fuel Tank	Fuel Tank
Fore Inter-Stage Adapter	Fore Inter-Stage Adapter	Fore Inter-Stage Adapter
Aft Skirt	Inter-Tank Adapter	Inter-Tank Adapter
Inter-Tank Adapter	Thrust Structure	Thrust Structure
Thrust Structure	Oxidizer Tank Insulation*	Payload Fairing
Oxidizer Tank Insulation*	Fuel Tank Insulation*	Oxidizer Tank Insulation*
Fuel Tank Insulation*	Base Heat Shield	Fuel Tank Insulation*
Base Heat Shield	Main Engines	Base Heat Shield
Main Engines	Propellant Feed Lines	Main Engines
Propellant Feed Lines	Gimbal	Propellant Feed Lines
Gimbal	Main Propellant Residuals	Gimbal
Main Propellant Residuals	Main Propellant Reserves	RCS Engines
Main Propellant Reserves	Main Propellant Pressurant	RCS Oxidizer Tank
Main Propellant Pressurant		RCS Fuel Tank
		RCS Propellant Feed Lines
		Guidance & Navigation
		Communication & Tracking
		Data Processing
		Thermal Control System
		Ordinance
		Main Propellant Residuals
		Main Propellant Reserves
		Main Propellant Pressurant
		RCS Propellant
		RCS Residuals
		RCS Reserves
		RCS Pressurant

* Cryogenic propellants only

Table 10: Inert components included in each stage for a four stage solid propellant rocket

Stage 1	Stage 2	Stage 3	Stage 4
Fore Inter-Stage Adapter	Fore Inter-Stage Adapter	Fore Inter-Stage Adapter	Fore Inter-Stage Adapter
Motor Case	Motor Case	Motor Case	Payload Fairing
Motor Nozzle	Motor Nozzle	Motor Nozzle	Motor Case
Motor Igniter	Motor Igniter	Motor Igniter	Motor Nozzle
Motor Insulation	Motor Insulation	Motor Insulation	Motor Igniter
Aft Skirt			Motor Insulation
			RCS Engines
			RCS Oxidizer Tank
			RCS Fuel Tank
			RCS Propellant Feed Lines
			Onboard Computers
			RCS Propellant
			RCS Residuals
			RCS Reserves
			RCS Pressurant

The ΔV requirement is shared evenly across all stages, as is the theoretical optimum for multiple stages with the same I_{sp}. (Larson, Pranke et al. 2007) Though I_{sp} changes slightly with change in altitude, for the same propellant combinations it is assumed in this analysis to be constant.

The same ΔV is assumed for all rockets. According to (Humble, Henry et al. 1995), the ΔV required to achieve LEO of several common rocket systems is 8.8-9.3 km/s. These values consider and include the ideal ΔV required to achieve LEO, losses due to gravity, thrust vectoring, and drag, and gains due to the rotation of the Earth. Choosing an arbitrary ΔV requirement within this range, it is assumed all rockets must achieve a ΔV of 9 km/s (9,000 m/s).

4.5 Summary of Rocket Configurations Modeled for Analysis

In total, there are seventy different configurations: three liquid propellant combinations, each with two staging options and with ten payload mass options for each staging option, and one solid propellant combination with one staging option and ten different payload mass options. Each of the seventy rockets is initially sized, assuming no light-weighting. Then, each rocket is resized assuming some light-weighting of certain components. In total, seventy pairs of rockets, or 140 total rockets are considered for primary analysis. The different configurations are shown in Table 11, each to be initially assessed then light-weighted.

Several additional rocket pairs (one un-lightened and one lightened) representing different scenarios are considered during the analysis. These scenarios are not necessary to answering the research questions, but are done for the sake of interest and to see if there are certain factors that may influence environmental impacts that may warrant additional investigation beyond this particular research. These scenarios are discussed in detail in Chapter 11.

Table 11: Rocket configurations considered, assuming a ΔV of 9,000 m/s

Payload Mass (kg)	Total Impulse (MM kg-m/s)	Two Stages	Three Stages	Four Stages
500	4.50	*(not sized)*	*(not sized)*	Solid
750	6.75	*(not sized)*	*(not sized)*	Solid
1,000	9.00	*(not sized)*	*(not sized)*	Solid
1,250	11.25	*(not sized)*	*(not sized)*	Solid
1,500	13.50	*(not sized)*	*(not sized)*	Solid
1,750	15.75	*(not sized)*	*(not sized)*	Solid
2,000	18.00	*(not sized)*	*(not sized)*	Solid
2,250	20.25	*(not sized)*	*(not sized)*	Solid
2,500	22.50	LOX/LH2	LOX/LH2	Solid
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
5,000	45.00	LOX/LH2	LOX/LH2	Solid
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
10,000	90.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
20,000	180.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
35,000	315.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
50,000	450.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
75,000	675.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
100,000	900.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
150,000	1,350.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
200,000	1,800.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	

4.6 The Parametric Rocket Sizing Model

4.6.1 Description of the Parametric Rocket Sizing Model

The *Parametric Rocket Sizing Model* (PRSM) is a parametric model that estimates the size (mass) of the various major inert components of a rocket identified in the previous sections as well as the mass of propellants. Masses are required for the LCA as most database entries for materials, fuels, and processes are given on a per-unit-mass basis. Once a component is sized, a material and a manufacturing method are assigned and the appropriate life cycle inventory information is attributed to it.

The PRSM calculates component masses using *Mass Estimating Relationships* (MER's). The MER's are mathematical regressions based on historic data that estimate the mass of a particular component as a function of some known or previously determined parameter. Many of the MER's used are found in the literature, but some MER's had to be developed based on gathered data.

Using the PRSM enables a large number of rockets to be sized consistently under the same assumptions, ensuring that results are precise and repeatable. Different parameters can be isolated and varied under controlled circumstances to help establish any trends and determine causes of these trends more conclusively.

Several parameters must be assumed before the rocket can be sized. The total impulse the rocket delivers to the payload must be defined, done in this procedure by determining the desired ΔV and assuming some payload mass. Next, properties of the propulsion system are required. This includes which propellants are used, density of these propellants, oxidizer to fuel ratio (O/F ratio) for liquid propellants, specific impulse (I_{sp}) of the engines, and desired thrust-to-weight ratio. Finally, the number of desired stages is required. These parameters can be varied to see their role in and influence on determining environmental impacts.

An initial guess is used to estimate the total size of the rocket. Using the results from this initial guess, MER's are used to calculate specific component masses. The calculated component masses are then used to calculate a new guessed value for the overall size of the rocket. This process continues, iteratively, until the guessed rocket size and the calculated rocket size converge.

To represent light-weighting, certain components have their mass reduced by some factor. The rocket must be resized to reflect the reduction in structural mass since a lower structural mass requires less propellant to launch, which in turn requires an even lower structural mass. The new rocket is resized using the same iterative process as before.

4.6.2 Required Input Parameters

Several inputs are required to size each rocket. First, the mass of the payload is required, and this is selected (one at a time) from the list of payloads under consideration in Section 4.4.1 (beginning on page 71). Next, the required ΔV of the rocket is required, set here at 9,000 m/s. As discussed earlier, the ΔV is divided evenly amongst all stages. Each stage of a two stage rocket provides a ΔV of 4,500 m/s, each stage of a three stage rocket delivers a ΔV of 3,000 m/s, and each stage of a four stage rocket delivers a ΔV of 2,250 m/s. Properties about the propulsion system are also required. The assumed properties of the different propellants are given in Table 6 (beginning on page 73).

4.6.3 Calculation Procedure in the Parametric Rocket Sizing Model

The procedure for sizing a rocket is fundamentally the same for each of the configurations summarized in Table 11 (page 81), despite different payload masses, propellants, or number of stages. The procedure starts by sizing the final stage of the rocket and works backwards (downwards) towards earlier stages of the rocket, ending with the first stage. The general procedure is shown graphically in Figure 12.

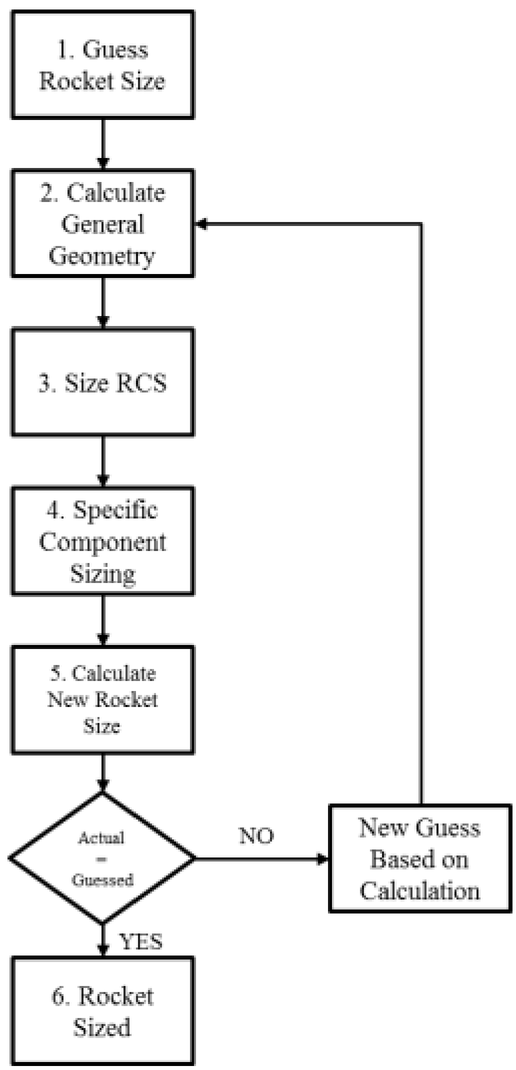


Figure 12: Graphical representation of rocket sizing procedure

The detailed rocket sizing procedure is as follows:

1. An initial guess for the properties of the stage is made, assuming ΔV is shared equally between the stages.

a. The *Mass Ratio* (MR) of the rocket is calculated.

$$MR = e^{\frac{\Delta V}{g_0 I_{sp}}} \tag{2}$$

b. The *Inert Mass Fraction* (f_{inert} or IMF) of the stage is initially guessed to be 0.1.

c. The total propellant mass (m_{prop}) for the stage is estimated.

$$m_{prop} = \frac{m_{pl}(MR-1)(1-f_{inert})}{1-f_{inert}MR} \tag{3}$$

d. The inert mass (m_{inert}) of the stage is estimated.

$$m_{inert} = \frac{f_{inert}}{1-f_{inert}} m_{prop} \tag{4}$$

e. The total mass or gross mass (m_{gross}) of the stage, including payload, is calculated.

$$m_{gross} = m_{pl} + m_{prop} + m_{inert} \tag{5}$$

2. Some general geometric properties, like lengths, areas, and volumes of the stage are then calculated.

a. For liquid propellants, the individual masses of the oxidizer (m_{ox}) and fuel (m_{fuel}) can be calculated. This step is not needed for solid propellants

$$m_{ox} = \frac{m_{prop}(O/F)}{1+(O/F)} \tag{6}$$

$$m_{fuel} = m_{prop} - m_{ox} \tag{7}$$

b. Volume of each propellant is calculated.

$$V = \frac{m}{\rho} \tag{8}$$

c. The diameter (D) of the stage is approximated as a function of total propellant volume (V_{tot}), according to Appendix A.

$$D = 0.4169 V_{tot}^{0.3554} \tag{9}$$

d. For liquid propellants, surface area of each of the propellant tanks is estimated, assuming cylindrical tanks with spherical ends. This is not needed for solid propellants.

$$A_{tank,surface} = 4\pi\left(\frac{D}{2}\right)^2 + \frac{2\left(V - \frac{4}{3}\pi\left(\frac{D}{2}\right)^2\right)}{r} \tag{10}$$

e. Base area of the stage is calculated.

$$A_{base} = \pi\left(\frac{D}{2}\right)^2 \tag{11}$$

f. The required thrust (T) for the second stage is calculated, assuming a thrust to weight ratio (T/W) of 1.35.

$$T = m_{gross} g_0 (T/W) \tag{12}$$

3. The RCS is sized using a similar procedure as Steps 1a-1c and 2a-2b. N2O4/UDMH is always assumed to be the RCS propellant combination. The f_{inert} for the RCS is fixed at 0.1.

4. The MER's for each of the components of the stage, found in Appendix A, are used to calculate the mass of the components, using parameters calculated in earlier steps.

5. A new structural mass is calculated for the second stage.

a. The masses of inert components calculated using the MER's are summed.

b. The newly calculated total inert mass is compared to the original guess calculated in Step 1d. If the inert masses are adequately close, the stage is sized and the procedure repeats for the next stage.

c. If the inert masses are not equal, a new f_{inert} is calculated. Steps 1-5b are repeated until the stage is sized.

$$f_{inert} = \frac{m_{inert}}{m_{inert} + m_{prop}} \tag{13}$$

6. Steps 1-5 are repeated to size each stage of the rocket, assuming the complete stage of all following stages are the effective payload for the stage being sized.

It was found that the process converged for all 140 rockets sized in 20 iterations or less.

4.6.4 Light-Weighting

To represent light-weighting, certain components have their mass adjusted by a factor. This factor is arbitrarily chosen to be 0.75 (75%) of the original mass of the component. In other words, it is assumed light-weighting with CFRP's can reduce the mass of a metal component by 25%. This assumption is made based on literature According to Duflou et al., light-weighting a steel component with CFRP's reduced the weight of the component by about 50%, while (Suzuki and Takahashi undated) assumed and average reduction in mass of 39.1%, while individual component mass reductions ranged from 17.9% to 57.3%. Chapter 11 investigates what occurs if these components are light-weighted by different amounts. The environmental impacts are reassessed assuming a mass reduction of as little as 10% and as high as 50%, representing the types of reductions expected from literature.

Not all components in a rocket can be light-weighted with CFRP's. The components that are considered candidates for light-weighting are:

- Payload Fairing
- Fore Inter-Stage Adapter
- Aft Skirt
- Inter-Tank Adapter
- Motor Casing

The MER's for these components remain unchanged, save that they are now multiplied by 0.75. Each of the rockets is resized using the same procedure from the previous section with the appropriate MER's for the components listed above modified accordingly.

4.6.5 Results from Parametric Rocket Sizing Model

There are seventy different rocket configurations being considered given the different possible propellants, staging options, and lift capacities outlined earlier. Each of these rockets are sized assuming no light-weighting and no CFRP's are used. General results for the liquid rockets are seen in Table 12 and

Table 13 for the solid rockets in Table 14 and Table 15. Complete and detailed results from mass calculations for each of the configurations, broken down into individual components, can be found in Appendix C.

Table 12: General results from the PRSM for liquid propellant rockets with payloads 2,500-35,000 kg to LEO, without light-weighting

Configuration	Payload Mass (kg)	2,500	5,000	10,000	20,000	35,000
	Total Impulse (MM kg-m/s)	**22.5**	**45**	**90**	**180**	**315**
LOX/LH2 2 Stage	Propellant Mass (kg)	90,415	154,355	281,148	533,036	909,066
	Inert Mass (kg)	20,812	34,570	61,739	115,521	195,610
	Total Mass (kg)	113,727	193,926	352,887	668,557	1,139,676
LOX/LH2 3 Stage	Propellant Mass (kg)	67,525	115,312	210,304	399,342	681,893
	Inert Mass (kg)	17,210	28,361	50,418	94,131	159,277
	Total Mass (kg)	87,235	148,673	270,722	513,473	876,170
LOX/RP1 2 Stage	Propellant Mass (kg)	200,315	350,951	651,399	1,251,108	2,149,674
	Inert Mass (kg)	25,219	43,509	79,949	152,638	261,527
	Total Mass (kg)	228,034	399,460	741,348	1,423,746	2,446,201
LOX/RP1 3 Stage	Propellant Mass (kg)	136,433	239,624	445,614	857,022	1,473,639
	Inert Mass (kg)	18,732	32,257	59,220	113,025	193,645
	Total Mass (kg)	157,666	276,881	514,834	990,048	1,702,284
N2O4/UDMH 2 Stage	Propellant Mass (kg)	226,536	389,085	714,388	1,365,781	2,344,113
	Inert Mass (kg)	24,463	41,205	74,740	141,963	243,039
	Total Mass (kg)	253,499	435,291	799,128	1,527,744	2,622,152
N2O4/UDMH 3 Stage	Propellant Mass (kg)	157,537	269,442	493,335	941,472	1,614,227
	Inert Mass (kg)	18,419	30,569	54,903	103,675	176,992
	Total Mass (kg)	178,456	305,011	558,238	1,065,147	1,826,220

Table 13: General results from the PRSM for liquid propellant rockets with payloads 50,000-200,000 kg to LEO, without light-weighting

Configuration	Payload Mass (kg)	50,000	75,000	100,000	150,000	200,000
	Total Impulse (MM kg-m/s)	**450**	**675**	**900**	**1,350**	**1,800**
LOX/LH2 2 Stage	Propellant Mass (kg)	1,284,048	1,907,786	2,530,616	3,774,749	5,017,700
	Inert Mass (kg)	275,363	407,890	540,132	804,141	1,067,792
	Total Mass (kg)	1,609,411	2,390,677	3,170,747	4,728,890	6,285,492
LOX/LH2 3 Stage	Propellant Mass (kg)	963,858	1,433,106	1,901,844	2,838,458	3,774,403
	Inert Mass (kg)	224,180	332,069	439,751	654,778	869,549
	Total Mass (kg)	1,238,038	1,840,175	2,441,595	3,643,236	4,843,951
LOX/RP1 2 Stage	Propellant Mass (kg)	3,047,838	4,544,553	6,041,303	9,035,348	12,030,297
	Inert Mass (kg)	370,372	551,786	733,249	1,096,371	1,459,753
	Total Mass (kg)	3,468,210	5,171,339	6,874,553	10,281,719	13,690,049
LOX/RP1 3 Stage	Propellant Mass (kg)	2,090,042	3,117,235	4,144,404	6,198,903	8,253,729
	Inert Mass (kg)	274,239	408,570	542,934	811,789	1,080,813
	Total Mass (kg)	2,414,282	3,600,805	4,787,337	7,160,692	9,534,542
N2O4/UDMH 2 Stage	Propellant Mass (kg)	3,323,457	4,957,292	6,592,629	9,866,629	13,143,993
	Inert Mass (kg)	344,311	513,407	682,793	1,022,207	1,362,269
	Total Mass (kg)	3,717,768	5,545,699	7,375,423	11,038,835	14,706,262
N2O4/UDMH 3 Stage	Propellant Mass (kg)	2,287,425	3,410,113	4,533,452	6,781,562	9,031,115
	Inert Mass (kg)	250,438	373,047	495,844	741,851	988,273
	Total Mass (kg)	2,587,862	3,858,161	5,129,297	7,673,412	10,219,388

Table 14: General results from the PRSM for solid propellant rockets with payloads 500-1,500 kg to LEO, without light-weighting

Configuration	Payload Mass (kg)	500	750	1,000	1,250	1,500
	Total Impulse (MM kg-m/s)	**4.5**	**6.75**	**9**	**11**	**14**
Solid 4 Stage	Propellant Mass (kg)	27,748	38,097	48,571	59,156	69,838
	Inert Mass (kg)	2,256	3,134	4,057	5,020	6,017
	Total Mass (kg)	30,504	41,981	36,865	65,425	77,354

Table 15: General results from the PRSM for solid propellant rockets with payloads 1,750-5,000 kg to LEO, without light-weighting

Configuration	Payload Mass (kg)	1,750	2,000	2,250	2,500	5,000
	Total Impulse (MM kg-m/s)	**15.75**	**18**	**20.25**	**23**	**45**
Solid 4 Stage	Propellant Mass (kg)	80,607	91,455	102,377	113,368	226,324
	Inert Mass (kg)	7,045	8,102	9,185	10,294	22,495
	Total Mass (kg)	89,402	101,557	113,813	126,162	253,819

Light-weighting a component initially reduces the mass of that component. For instance, a 100 kg component, light-weighted under the assumptions presented earlier, would have a mass of 75 kg after light-weighting. The *initial reduction in inert mass* is 25 kg. A lighter inert mass requires a smaller quantity of propellant to achieve the same desired ΔV, thus reducing the total propellant mass. This smaller quantity of propellants requires less supporting structure, further reducing the inert mass of the rocket. This process goes on iteratively to a limit when the rocket is resized. At this point, there is some *total reduction in inert mass after iterating* that is some quantity higher than the initial 25 kg. Likewise, there is a *total reduction in propellant mass after iterating*, and consequently a *total reduction in gross mass after iterating*. The total final reductions in mass depend on the payload mass, propellants used, and the number of stages.

Table 16, Table 17, Table 18, and Table 19 tabulate the initial reduction in inert mass after light-weighting for each of the 70 different rocket configurations. Also shown for each configuration is the total reduction in inert mass, propellant mass, and gross mass that results after iterating to resize the rocket.

Table 16: Final reductions after iterating to resize in inert mass, propellant mass, and gross mass of a rocket after some initial reduction in inert mass due to light-weighting the LOX/LH2 propellant rockets

Payload to LEO (kg)	Stages	Initial Reduction in Inert Mass (kg)	Total Reductions After Iterating		
			Inert Mass (kg)	Propellant Mass (kg)	Gross Mass (kg)
2,500	2	181	794	2,960	3,753
	3	168	643	2,130	2,773
5,000	2	338	1,534	5,803	7,338
	3	318	1,247	4,193	5,440
10,000	2	647	2,980	11,359	14,339
	3	614	2,438	8,268	10,706
20,000	2	1,254	5,831	22,360	28,191
	3	1,197	4,793	16,364	21,156
35,000	2	2,152	10,065	38,740	48,805
	3	2,061	8,297	28,447	36,745
50,000	2	3,040	14,272	55,044	69,316
	3	2,918	11,785	40,494	52,279
75,000	2	4,508	21,250	82,122	103,372
	3	4,338	17,576	60,526	78,102
100,000	2	5,966	28,202	109,124	137,326
	3	5,749	23,350	80,522	103,872
150,000	2	8,860	42,055	162,990	205,045
	3	8,555	34,866	120,448	155,315
200,000	2	11,736	55,866	216,736	272,602
	3	11,347	46,357	160,318	206,675

Table 17: Final reductions after iterating to resize in inert mass, propellant mass, and gross mass of a rocket after some initial reduction in inert mass due to light-weighting the LOX/RP1 propellant rockets

Payload to LEO (kg)	Stages	Initial Reduction in Inert Mass (kg)	Total Reductions After Iterating		
			Inert Mass (kg)	Propellant Mass (kg)	Gross Mass (kg)
2,500	2	169	962	6,726	7,688
	3	156	720	4,468	5,188
5,000	2	321	1,881	13,249	15,130
	3	301	1,416	8,857	10,273
10,000	2	621	3,706	26,218	29,924
	3	587	2,801	17,604	20,404
20,000	2	1,211	7,333	52,048	59,381
	3	1,152	5,558	35,054	40,612
35,000	2	2,085	12,752	90,676	103,428
	3	1,991	9,682	61,184	70,867
50,000	2	2,952	18,158	129,238	147,396
	3	2,825	13,800	87,289	101,089
75,000	2	4,387	27,153	193,428	220,581
	3	4,208	20,654	130,767	151,421
100,000	2	5,813	36,137	257,561	293,698
	3	5,585	27,504	174,223	201,727
150,000	2	8,648	54,087	385,731	439,818
	3	8,326	41,194	261,102	302,296
200,000	2	11,467	72,024	513,830	585,854
	3	11,055	54,879	347,957	402,836

Table 18: Final reductions after iterating to resize in inert mass, propellant mass, and gross mass of a rocket after some initial reduction in inert mass due to light-weighting the N2O4/UDMH propellant rockets

Payload to LEO (kg)	Stages	Initial Reduction in Inert Mass (kg)	Total Reductions After Iterating		
			Inert Mass (kg)	Propellant Mass (kg)	Gross Mass (kg)
2,500	2	171	889	7,212	8,101
	3	158	659	4,820	5,479
5,000	2	323	1,750	14,318	16,068
	3	303	1,302	9,615	10,917
10,000	2	623	3,460	28,418	31,878
	3	589	2,582	19,150	21,732
20,000	2	1,214	6,870	56,573	63,442
	3	1,154	5,138	38,204	43,342
35,000	2	2,090	11,976	98,756	110,732
	3	1,995	8,968	66,771	75,739
50,000	2	2,958	17,078	140,912	157,990
	3	2,831	12,796	95,331	108,126
75,000	2	4,395	25,575	211,146	236,721
	3	4,215	19,175	142,924	162,098
100,000	2	5,824	34,070	281,362	315,432
	3	5,594	25,553	190,514	216,067
150,000	2	8,664	51,056	421,777	472,833
	3	8,339	38,311	285,696	324,007
200,000	2	11,488	68,042	562,188	630,230
	3	11,072	51,070	380,884	431,955

Table 19: Final reductions after iterating to resize in inert mass, propellant mass, and gross mass of a rocket after some initial reduction in inert mass due to light-weighting the solid propellant rockets

Payload to LEO (kg)	Stages	Initial Reduction in Inert Mass (kg)	Total Reductions After Iterating		
			Inert Mass (kg)	Propellant Mass (kg)	Gross Mass (kg)
500	4	257	370	1,677	2,047
750	4	381	558	2,519	3,077
1,000	4	514	761	3,398	4,160
1,250	4	654	978	4,313	5,290
1,500	4	802	1,206	5,258	6,464
1,750	4	955	1,444	6,231	7,676
2,000	4	1,115	1,693	7,230	8,923
2,250	4	1,280	1,950	8,253	10,204
2,500	4	1,449	2,217	9,298	11,515
5,000	4	3,370	5,280	20,759	26,040

It can be seen that some relatively small initial light-weighting of a rocket lead to significantly larger reductions in the overall rocket mass. The results for light-weighting each of these configurations, broken down into components, can also be found in Appendix B. Detailed discussion about the effects of light-weighting on the rocket's total mass and the resulting changes to the environmental impacts are discussed in Chapter 7 (beginning on page 144).

4.7 Comparison of Rocket Sizing Results to Real World Systems

4.7.1 Expected Model Limitations

The PRSM makes certain assumptions for simplification that may not reflect real world systems precisely. One major assumption is that several parameters, such as propellants used, I_{sp}, initial T/W ratio of the stage, and O/F ratio of the propellants are the same for each stage. Another major assumption is that the ΔV is split evenly across all of the stages.

Many real world systems use different propellant combinations for different stages, even using solid boosters with liquid core rockets. The I_{sp} also tends to change during flight, increasing with altitude. Parameters like T/W ratio and O/F ratio can also change from rocket to rocket. While optimizing all of these parameters, real world systems divide the total ΔV unequally amongst the different stages. The model also does not take into account different launch latitudes or final orbit inclinations, which could change sizing results. All of these variations can lead to model inaccuracies.

The MER's that the PRSM relies on during calculations are also approximations. They are historical regressions, though they do not represent historical data perfectly. There is some margin of error that is expected when applying the MER's. This issue is addressed during the uncertainty analysis performed in Chapter 10 (beginning on page 239).

4.7.2 Comparison to Real World Systems

As discussed in the previous section, there are many variables that can cause the modeled mass of a particular rocket to be different from the mass of an actual rocket with similar performance. It would be difficult, if not impossible to make a perfect comparison between a rocket modeled using the PRSM and an actual rocket with similar performance. Nevertheless, the results of the PRSM are compared to similar real world systems as best as possible to determine whether the model does an adequately good job sizing a rocket.

Three liquid propellant options were assessed, each with two staging options. Though a wide range of payloads were also assessed for each of these six propellant and stage combinations, the comparison is limited here to several particular cases. The overall size (gross mass) of several real world rockets was compared to similar rockets sized by the PRSM. These results are found in Table 20.

Table 20: Comparison of actual liquid rockets to rockets sized using the PRSM

Configuration	Rocket	Payload to LEO (kg)	Gross Mass (kg)		Difference (%)
			Actual	Modeled	
LOX/LH2, 2 Stage	Delta IV (United Launch Alliance 2007)	8,500	257,000	305,320	-18.80%
LOX/LH2, 3 Stage	*(no adequate real world analog found)*				
LOX/RP1, 2 Stage	Falcon 9 (SpaceX 2009)	4,000	333,000	330,953	0.61%
LOX/RP1, 3 Stage	Zenit-3 SL (State Space Agency of Ukraine 2013)	6,100	462,200	329,269	28.76%
N2O4/UDMH, 2 Stage	Tsyklon (Lindborg undated)	3,000	182,000	289,885	-59.28%
N2O4/UDMH, 3 Stage	Dnepr-1 (ISC Kosmotras 2001)	4,500	211,000	279,700	-32.56%

The PRSM was unable to duplicate the overall gross mass of real world rockets exactly. The error in sizing some of the rockets is rather large, but the sizing results are still useful in this analysis. The PRSM is understood to be an approximation and the results are still plausible. The uncertainty analysis in Chapter 10 (starting on page 239) accounts for errors as large as ±50% in the PRSM results and data. In Chapter 10, it was found that the error in Table 20 is acceptable and does not change the answers to the research questions.

The best results were modeling the two stage LOX/RP1 rocket. The PRSM quite closely predicted the total mass of a Falcon 9 rocket. This is appropriate as the Falcon 9 is quite modern with an all metal construction (prime for light-weighting with carbon fiber composites). Though some of the other rockets are still in use today, they are considerably older designs. The oldest, and incidentally the worst approximated by the PRSM, is the Tsyklon.

The solid propellant rockets sized by the PRSM were all assumed to have four stages and payload masses to LEO between 500 and 5,000 kg. There are four real world rockets that have these same basic characteristics: the Taurus, Minotaur I, Minotaur IV, and Start-1 rockets. A comparison of model results can be seen in Table 21.

Table 21: Comparison of actual solid rockets to rockets sized using the PRSM

Rocket	Payload to LEO (kg)	Gross Mass (kg)		Difference (%)
		Actual	Modeled	
Start-1 (United Start 2006)	532	47,200	31,964	-32.28%
Minotaur I (Orbital Science Corporation 2006)	580	36,200	34,158	-5.64%
Taurus (Orbital Science Corporation 2006)	1,320	73,000	68,753	-5.82%
Minotaur IV (Orbital Science Corporation 2006)	1,735	86,300	88,677	2.75%

It can be seen that the model did a much better job with the solid propellant rockets than the liquid propellant rockets in predicting their masses. For the same payload to LEO (approximately 400 km circular altitude, with a ΔV of ~9,000 m/s), the PRSM did not compare well to the Start-1 rocket. However, this rocket exhibits some peculiarities. The rocket's gross mass is much higher than that of the Minotaur I, despite launching a lighter payload to LEO. According to their respective user's manual, the rocket has a much higher T/W than any of the other three rockets. Plugging in a higher T/W (2.75 instead of 1.35) predicts the Start-1's mass to be 45,459 kg. This is much closer to the expected gross mass.

The PRSM was able to predict the mass of the Taurus rocket relatively closely. The Taurus user's guide provides some more information about propellant mass and thrust for each stage, allowing for a more detailed comparison, shown in Table 22.

Table 22: Stage by stage comparison of the Taurus rocket to a similar rocket sized by the PRSM

Stage	Propellant Mass (kg)		Inert Mass (kg)		Inert Mass Fraction		Max. Vacuum Thrust (kN)	
	Actual	Modeled	Actual	Modeled	Actual	Modeled	Actual	Modeled
1	48,960	38,016	4,211	3,065	0.079	0.075	1,904	910
2	12,147	15,301	1,088	1,077	0.082	0.066	554	366
3	3,024	6,244	345	390	0.102	0.059	134	150
4	770	2,576	203	763	0.209	0.229	36	62
Total	*64,901*	*62,137*	*5,847*	*5,295*	*0.083*	*0.079*	*(n/a)*	

For the Taurus rocket, the PRSM managed to predict the total rocket mass, total propellant mass, and total inert mass fairly closely, but was unable to size each individual stage very well. Looking more closely at the Taurus rocket, it becomes clear that there are two things the PRSM does not account for, contributing to the discrepancies. Firstly, the Taurus rocket does not split its total impulse, or ΔV, evenly across all four stages, as is assumed to be the case in the PRSM. The PRSM also assumes that the I_{sp} for each stage remains constant, which is not the case in real world system like the Taurus rocket.

This means that the real world ΔV split would not be even across all stages. Secondly, the initial T/W is different for each stage of the Taurus rocket; whereas, the initial T/W is assumed to be the same across all stages in the PRSM. Despite the discrepancies for each individual stage, it is found that the PRSM did an adequate job in modeling a real world, four stage solid propellant rocket system such that an LCA on these results would provide useful and meaningful insight into a real world system's environmental impacts.

These comparisons provide a good gage as to how much error should be considered during the uncertainty analysis. Based on the above results, it is assumed that an uncertainty of ±10% would be the minimum expected, while an uncertainty of ±25% would come closely to bounding the results for a real world system. An uncertainty of ±50% would represent a gross miscalculation on the part of the PRSM, but would certainly bound the environmental performance of a real world system.

4.7.3 Conclusions About Parametric Rocket Sizing Model Usefulness and Validity

It is concluded that the PRSM is capable of adequately estimating the mass of various rocket components. Though error between calculated masses and real-world masses were identified, it is important to note the complexity and diversity found in rockets. There is no one formula that can size a rocket exactly and many considerations must be taken into account when accurately sizing a real world rocket.

The rockets sized by the PRSM are found to be plausible and realistic when compared to real world systems. Different parameters of the PRSM can be tweaked to more accurately predict the mass of a rocket, but it is not thought that this additional detail would bring additional insight into the environmental performance of rocket systems for the purpose of answering the two motivating questions in this research.

4.8 Chapter Summary

This chapter defined the specific rocket configurations that are being considered in this analysis. Four different propellant options are considered, including three liquid propellant combinations and one solid propellant. Three different staging options are also considered, representing a wider range of rockets. Finally, the lift capacities of each rocket configuration are outlined. In total, 70 different rocket configurations are assessed initially as the baseline for comparison. These 70 rockets are then light-weighted and the result on their lifetime environmental impacts are compared to their baseline companion.

The Parametric Rocket Sizing Model was also defined in this chapter. The PRSM determines the overall size of a rocket as well as the size of individual components as a function of inputs that represent the propellants used and number of stages used. This model is useful because it allows for the consistent and repeatable sizing of a wide range of different rocket configurations. Parameters can be changed in a controlled manner to determine if changes to the lifetime impacts are the result of light-weighting or of some other influence. Being able to model and assess many different rocket configurations helps bring insight into a wide range of real world rockets and solidify the relationship, if any, between light-weighting and reduction in impacts.

5 LIFE CYCLE INVENTORY: PROPELLANTS

5.1 Overview of Chapter Contents

This chapter outlines the life cycle inventory for the different propellants under consideration. Since data for some propellants is found in existing databases, and since the propellants themselves can arguably be considered resources, this chapter focuses on aspects of propellant production that can span the rocket's material harvesting phase and manufacturing phase. The primary way in which each propellant is produced is discussed. This description is more of a qualitative definition of each propellant's life cycle inventory. If an existing inventory can be used from a database, the specific entry used is given in each section while detailed inventory information can be found in Appendix C for those that require a manually created inventory. This chapter summary compiles all of the inventory entries in a single table (Table 27 on page 124), giving the exact name of each entry in the database, and the database identification number as it can be found in SimaPro.

This chapter is important because it outlines all of the various inputs and outputs that can be expected during the production of propellants. These help identify the types of environmental burdens that are associated with propellant production and where these impacts can be expected. Such definition helps serve as a "sanity check" when considering the results from the LCA in Chapter 9.

5.2 Liquid Hydrogen (LH2)

Liquid hydrogen manufacturing processes are described in detail by (Caras 1963). The technologies for producing liquid hydrogen haven changed little over the years. One particular method (discussed below) for producing liquid hydrogen is commonly used and is assumed to be the process by which the LH2 is produced for the rockets being assessed.

Hydrogen gas can be produced by breaking off the hydrogen atoms in a hydrogen rich molecule through some sort of chemical reaction. Several materials can be used as a feedstock for the process, including water, ammonia, coal, methanol, and hydrocarbons like methane and naphtha. Availability and affordability of resources and energy determine the best feedstock to use in a particular plant or process.

A common process used for producing hydrogen destined to be used as rocket fuel is called *steam-hydrocarbon reforming*, which was used to produce liquid hydrogen for the Space Shuttle. (Busacca 1984) This process is shown graphically in Figure 13.

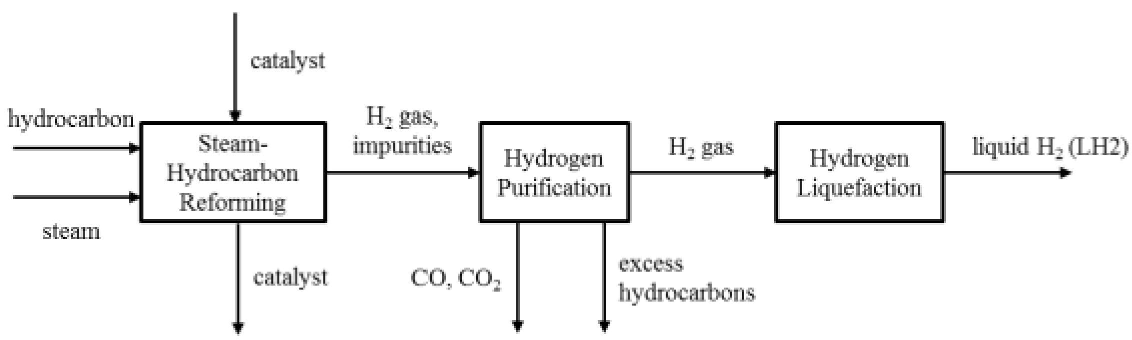


Figure 13: Representation of liquid hydrogen production process

In the steam-hydrocarbon reforming process, a hydrocarbon is mixed with steam and passed over a catalyst. The resulting reaction produces hydrogen gas and carbon monoxide. The carbon monoxide is typically oxidized to carbon dioxide in a subsequent process, producing additional hydrogen. A common hydrocarbon feedstock for this process is methane, which is rich in hydrogen atoms and is easily obtainable as natural gas. The methane is mixed with steam and passed over an aluminum oxide catalyst to produce hydrogen according to the following reactions. (Speight 2006)

$$CH_4 + H_2O \xrightarrow{Al_2O_3} CO + 3H_2 \quad (14)$$

$$CO + H_2O \xrightarrow{catalyst} H_2 + CO_2 \quad (15)$$

The oxidation of carbon monoxide to carbon dioxide using steam can be used asa stand-alone process called the *water-gas catalytic process*. It is more economical, though, to use it in conjunction with another process like the steam-hydrocarbon reforming process that already produces waste carbon monoxide that must be processed. (Caras 1963)

More complex hydrocarbons may be used in steam-hydrocarbon reforming. In parts of the world, such as Europe, where natural gas may not be as plentiful as in places like the United States, naphtha is often used in place of methane. The catalytic reaction that produces hydrogen is more complex than the reaction to produce hydrogen from methane, but the principles are the same. Naphtha is mixed with steam and passed over a catalyst. The result produces hydrogen and oxides of carbon.

Once hydrogen is produced through the steam-hydrocarbon reforming process, it must be purified to remove oxides of carbon, excess water, and unreacted hydrocarbons. Purification can be done relatively easily by taking advantage of hydrogen's low boiling point. The gasses are cooled and the impurities liquefy or freeze. This can be done in steps to isolate certain impurities which may be harvested as useful byproducts. The liquid or frozen impurities are easy to remove from the hydrogen gas at this stage.

The highly pure hydrogen gas must then be liquefied. Three common processes for liquefaction of hydrogen exist: the Liquid Expansion Cycle, the Joule-Thompson Expansion Process, and the Expansion Engine or Claude Cycle. No single process can be used to produce hydrogen in the volumes necessary for use in rockets. The liquefaction process typically combines or slightly modifies the three fundamental processes to achieve optimal liquid hydrogen production. The resulting product is ready to be used as a rocket propellant.

Liquid hydrogen is not considered a storable propellant and must be consumed relatively soon after it is produced to prevent significant losses. For this reason, LH2 ought to be produced a short distance from the launch site, close to the desired launch date. However, this has not always been the case in practice where the LH2 used for the Space Shuttle was produced in New Orleans, LA and then transported to Kennedy Space Center, FL by truck in insulated tanks. (Busacca 1984)

The steam-hydrocarbon reforming process can be energy intensive and has several major environmental burdens associated with it. The process consumes large quantities of hydrocarbons, which are not considered renewable resources. The process is also produces large amounts of carbon monoxide and carbon dioxide.

Multiple inventories for LH2 production are found in the EcoInvent database in SimaPro, including one process that produces liquid hydrogen primarily through steam-hydrocarbon reforming, which is identified above as being the likely means of LH2 production for the purposes of rocket fuel. This entry is found to be adequately representative of LH2 production destined to become a rocket propellant.

The specific entry for LH2 used is found under the name "Hydrogen, liquid, at plant/RER S" from the EcoInvent database.

5.3 Rocket Propellant-1 (RP-1)

Rocket Propellant-1, also referred to as Refined Petroleum-1, is highly refined kerosene similar to jet fuel. The basic production process is shown in Figure 14.

Kerosene can be refined a number of different ways and much of the process depends on the crude oil feed stock from which the kerosene is extracted. It is difficult to define a chemical formula for RP-1, but it can be defined here as kerosene refined to have a density of about 0.81 kg/l while containing very low levels of aromatics and sulfates. (Humble, Henry et al. 1995)

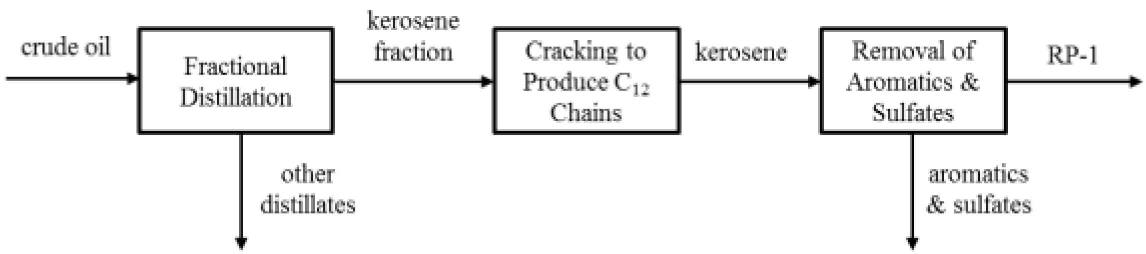


Figure 14: Representation of RP-1 production

Kerosene is produced though fractional distillation of crude oil. In the process of fractional distillation, the crude oil first passes through a furnace to vaporize most of the hydrocarbons. The resulting gasses are passed through a distillation tower where the temperature is reduced as the gasses travel up the tower. The different hydrocarbons contained in crude oil condense at different temperatures, allowing them to be isolated and removed at different levels of the tower. The crude oil fraction destined to become kerosene condenses at 126-258° C. These hydrocarbon chains contain between 8 and 18 carbon atoms. Ideally, the fraction destined to become RP-1 grade kerosene condenses at 205-260° C and has 12 carbon atoms per hydrocarbon chain. The kerosene must be refined to remove aromatics and sulfur compounds before being used as a rocket fuel. This improves storability of the kerosene, makes it less toxic than even diesel fuels or gasoline, and gives it a higher flash point. Kerosene with a very low sulfur and aromatic count resists thermal breakdown at higher temperatures and is more suited for use as a rocket propellant. (Speight 2006)

Since RP-1 is produced from kerosene distilled from crude oil, it shares many of the upstream cradle-to-gate (well-to-wheel) burdens of gasoline or diesel fuel. Several inventory entries in the EcoInvent database exist for the production of kerosene. Though it is unclear whether this kerosene has been processed to meet the specifications of RP-1 rocket propellant, it is assumed to be an adequate approximation for the purposes of this model.

The specific entry used for RP-1 is found under the name "Kerosene, at refinery/RER S" from the EcoInvent database.

5.4 Unsymmetrical Dimethylhydrazine (UDMH)

Hydrazine can be manufactured a number of different ways. One particular method of interest is the Olin-Raschig Process where chloramine is reacted with ammonia. To produce UDMH, the Olin-Raschig process is modified so that chloramine is instead reacted with dimethylamine. (Cicerone, Stedman et al. ; Schmidt 1984) The general process is depicted in Figure 15.

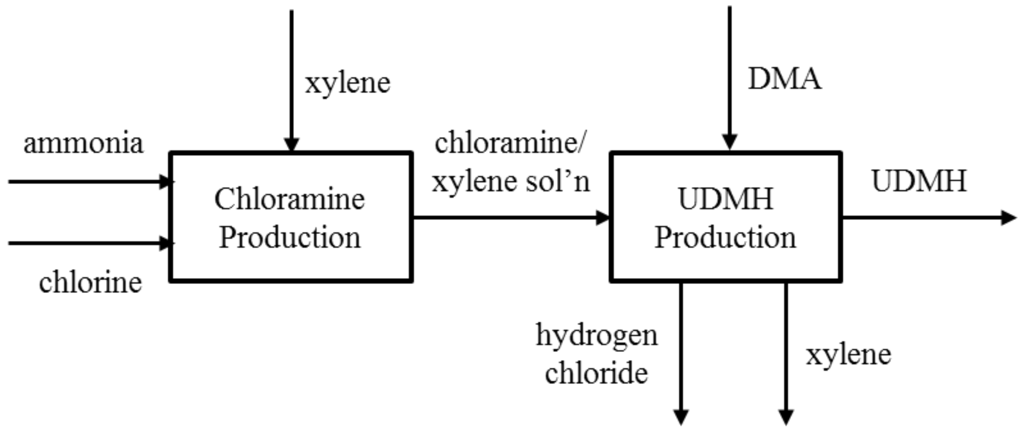


Figure 15: Representation of UDMH production

According to (Mueller, Farncomb et al. 1976), chloramine is most practically produced by reacting chlorine with an excess of ammonia and nitrogen gas at a temperature of 350° C according to the following reaction.

$$8\,NH_3 + \frac{1}{2}\,Cl_2 + \frac{1}{2}\,N_2 \rightarrow NH_2Cl + \frac{22}{3}\,NH_3 + \frac{1}{3}\,N_2 \tag{16}$$

The chloramine is absorbed by xylene, or a similar aromatic hydrocarbon like benzene or toluene. The excess ammonia is recycled and reused. The chloramine/xylene solution is mixed slowly with DMA at low temperatures to produce UDMH, as seen in the following reaction.

$$10\,DMA + NH_2Cl \xrightarrow[xylene]{} UDMH + 9\,DMA + HCl \tag{17}$$

The excess DMA is recovered and the UDMH is separated from the distilled xylene solution. The excess hydrogen chloride can be neutralized with sodium hydroxide to produce a more benign byproduct, but this is not necessary.

From an environmental standpoint, production of UDMH requires large amounts of ammonia for both the production of chloramine and DMA. This quantity of ammonia can be environmentally detrimental. Furthermore, the production of hydrogen chloride can be problematic if not properly neutralized.

An environmental LCI was assembled largely based on the UDMH production process description according to (Mueller, Farncomb et al. 1976). Process steps and parameters were confirmed by (Powell 1968) and (Schmidt 1984). This inventory entry is not as detailed as other inventory entries, but it must be used as no other LCI for the production of UDMH was found despite a thorough literature review.

The LCI for the production of UDMH is shown in Figure 16. The production of chloramine was not found in any of SimaPro's databases, so a unique entry for this had to be inserted, with the input and output flows shown. The complete inventories for both UDMH and chloramine production, as entered into newly created SimaPro entries, are found in Appendix C.

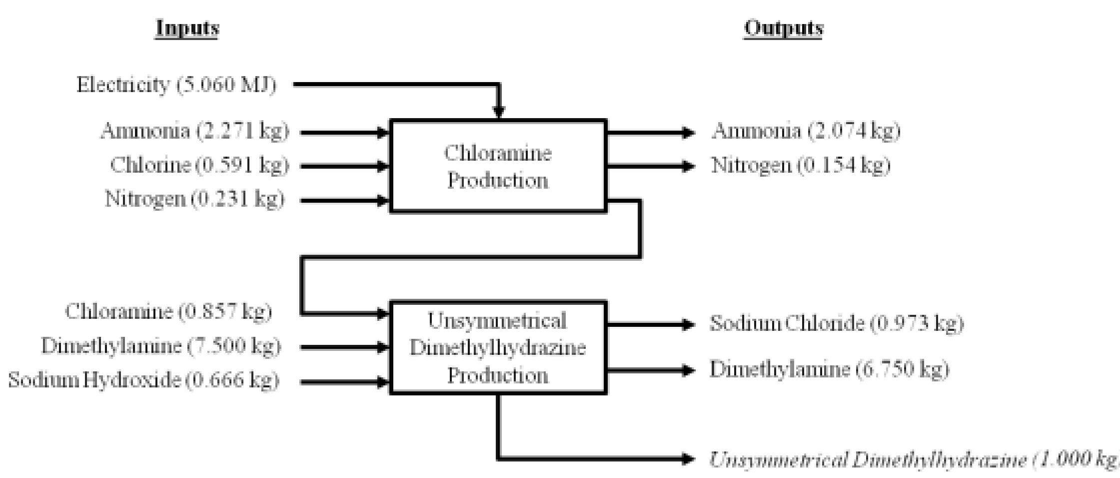


Figure 16: Production of 1 kg of unsymmetrical dimethylhydrazine

5.5 Liquid Oxygen (LOX)

Liquid oxygen is perhaps the simplest rocket propellant to produce. The process is shown graphically in Figure 17.

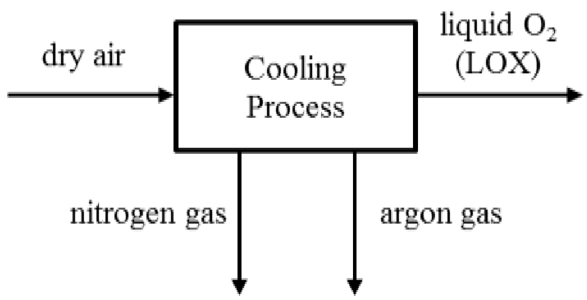


Figure 17: Representation of liquid oxygen production

Dry air contains roughly 78% nitrogen, 21% oxygen, and 1% argon, by volume, making it an excellent and readily available source for harvesting oxygen. Liquid oxygen is produced by cooling dry air slowly. Nitrogen, oxygen, and argon have different boiling points, of which oxygen's is the highest. This means that cooling air to a certain temperature will produce LOX while keeping the nitrogen and argon in the gas phase. The LOX is easy to separate from the remaining gasses and is of high purity. The process of cooling the gas can be repeated with the low quality oxygen (containing impurities) to try to increase its purity.

Liquid oxygen is not a storable propellant. Like hydrogen, it must be used shortly after it is produced to minimize waste.

Apart from the energy required for the liquefaction process, producing LOX is relatively environmentally benign. Nitrogen and argon are naturally found in air, so releasing these products has limited impact on the environment.

The EcoInvent database has entries for LOX production according to this process. As expected, the environmental burdens of LOX production are primarily caused by consuming energy during the liquefaction process or by operating and maintaining capital goods required for the process. One entry in the EcoInvent database is found to be adequately representative of the LOX production process outlined above as it defines an inventory for the distillation of air to produce liquid oxygen.

The specific entry for LOX used is named "Oxygen, liquid, at plant/RER S" from the EcoInvent database.

5.6 Nitrogen Tetroxide (N2O4)

Nitrogen tetroxide (N2O4) exists in equilibrium with nitrogen dioxide.

$$N_2O_4 \leftrightarrow 2\ NO_2 \tag{18}$$

At lower temperatures, the equation tends to the left and the concentration of N2O4 is increased. The liquid and solid states of the mixture are over 99.9% N2O4.(Roscoe and Hind 1993)

Nitrogen tetroxide is produced by first producing nitrogen dioxide, then chilling the gas to a liquid. The process is shown graphically in Figure 18.

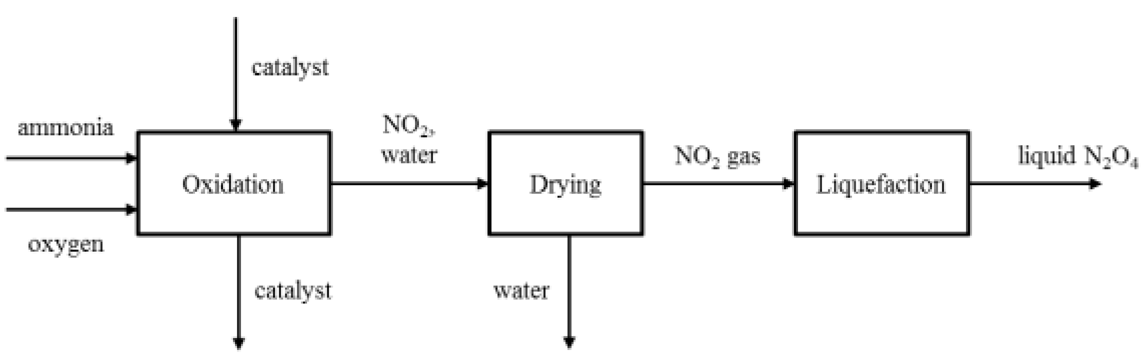


Figure 18: Representation of nitrogen tetroxide production

Nitrogen dioxide can be produced by the catalytic oxidation of ammonia (Kobe and Hosman 1948), according to the following equation. (Bell 1960)

$$4\,NH_3 + 7\,O_2 \xrightarrow{catalyst} 4\,NO_2 + 6\,H_2O \quad (19)$$

Platinum and rhodium can both be used as a catalyst. The reaction can tend to produce nitric oxide, unless excess oxygen is used. In practice, nitrogen dioxide is produced in a two-step process that first produced nitric oxide, and then oxidizes the nitric oxide to nitrogen dioxide.(Bell 1960)

The nitrogen dioxide is dried, removing the water and leaving high purity gas. The gas is then chilled to a liquid, which is high purity N2O4 ready to be used as a rocket propellant. Nitrogen tetroxide is considered a storable propellant. It can be produce some time ahead of a launch and it can be produced some distance from the launch site.

Apart for energy consumption during drying and cooling, consumption of ammonia contributes most heavily to the environmental burdens of N2O4. Furthermore, nitrogen dioxide hydrolyses with water and there is the potential for production of nitric acid. Ideally, only water is removed during the drying process, but the waste water may be treated with sodium hydroxide to neutralize the acid.

A literature survey was also not able to produce any environmental LCI for the production of N2O4. An LCI was developed based on the above process description. The quantified inputs and outputs for N2O4 production are shown in Figure 19, while the inputs for the newly created LCI entry in SimaPro are detailed in Appendix C.

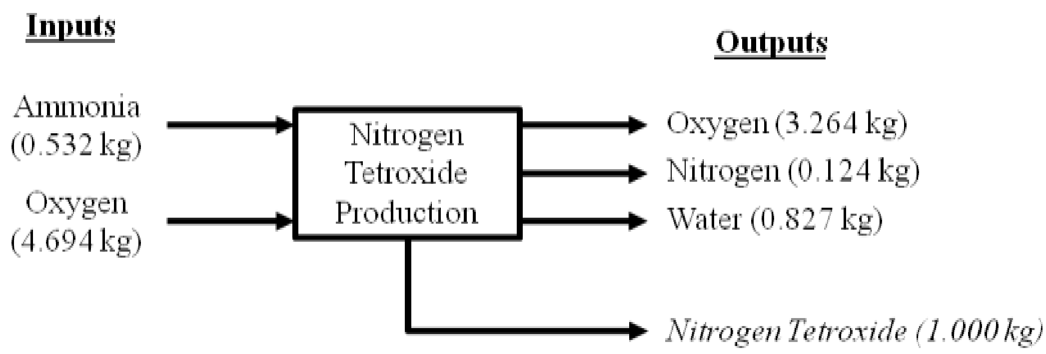


Figure 19: Life cycle inventory for the production of 1 kg of N2O4

5.7 Solid Propellant

The solid propellant formulation assumed in this research contains powdered aluminum fuel and an ammonium perchlorate oxidizer, held together with an HTPB binder. According to (Steinberger and Dreschel 1969), the process for producing solid propellants is rather simple. The majority of the process revolves around mixing the fuel and oxidizer and sizing it to the desired grain size. Once the grain is sized, it is cast into the correct shape using a binder to hold the grain together. In some cases, the grain is cast into a generic shape, then cut to the appropriate length and inserted into the motor casing. Once the binder has dried or cured, the propellant is ready for use. The simplified process is shown in Figure 20.

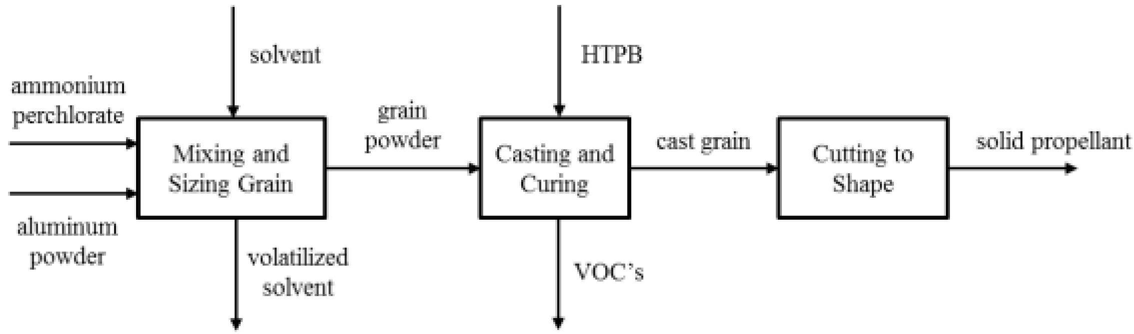


Figure 20: Graphical representation of solid propellant preparation

There is no pre-existing database entry for the preparation of solid propellants. Using the above diagram and information from literature, an LCI for the preparation of solid propellant was created, shown in Figure 21. Also required were the creation of LCI entries for ammonium perchlorate and perchloric acid as neither of these were found in the databases accessed by SimaPro. Complete entries for each of these, as input into SimaPro, can be found in Appendix C.

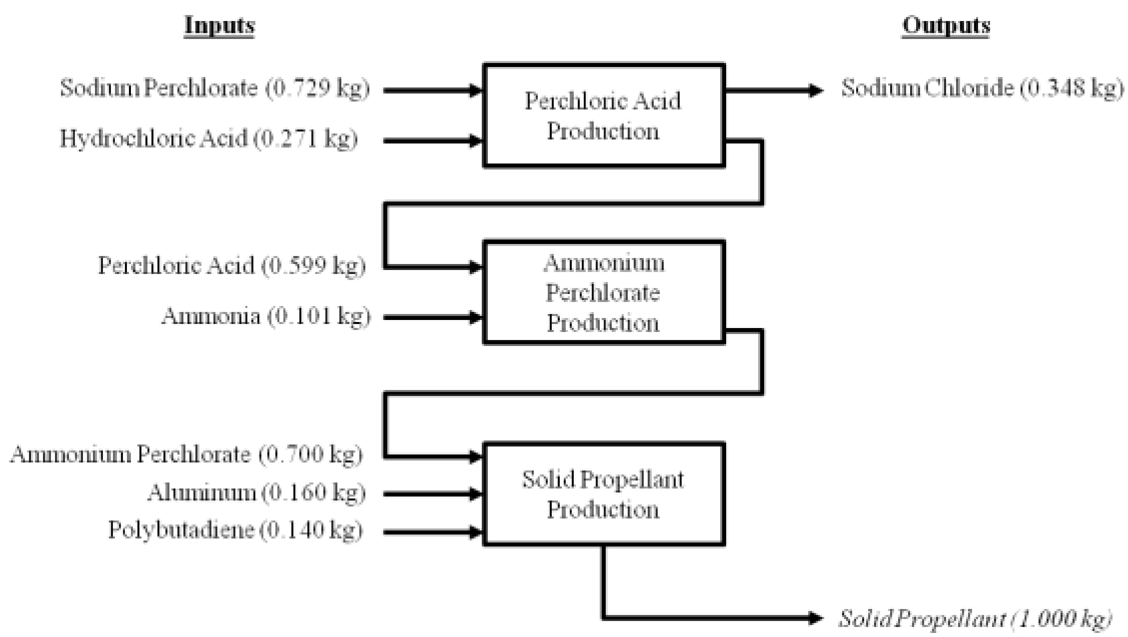


Figure 21: Life cycle inventory for the production of 1 kg of solid propellant

5.8 The Use Phase: Burning of Propellants

The rocket's use phase is assumed to be quite simple. The use phase begins with ignition of main engines during launch and ends with the payload being injected into orbit. During the use phase, propellants are consumed in a combustion reaction to generate thrust. The combustion products are released directly into the atmosphere. During use, spent stages are separated from the rocket and begin their fall to Earth. It is assumed that as soon as a stage separates, it has entered the end of life scenario and any impacts associated with it from that moment onward are allocated after the use phase.

SimaPro's databases do not contain entries for combustion of these rocket propellants, so an inventory of their exhaust products must be created. The inventory is made such that it represents the emissions produced while consuming 1 kg of propellants. The unit mass of propellants is assumed to be a combination of oxidizer and fuel in the appropriate O/F Ratio used for that particular combination. Exhaust products released from LOX/LH2 engine are calculated using chemical mass balance, while the inventory of exhaust products for LOX/RP1, N2O4/UDMH, and the solid propellant are found in literature (Kuzin 1997).

The calculations for the mass balance for the LOX/LH2 reaction is shown below. It is assumed that the O/F ratio is 5.5, meaning 5.5 kg of oxygen are mixed with 1 kg of hydrogen. This is a fuel rich mixture, meaning some hydrogen is left unconsumed. The combustion reaction is shown in Equation 20 (in moles). The flow diagram for the reaction, quantifying masses, is shown in Figure 22.

$$0.171875O_2 + 0.5H_2 \rightarrow 0.34375H_2O + 0.15625H_2 \tag{20}$$

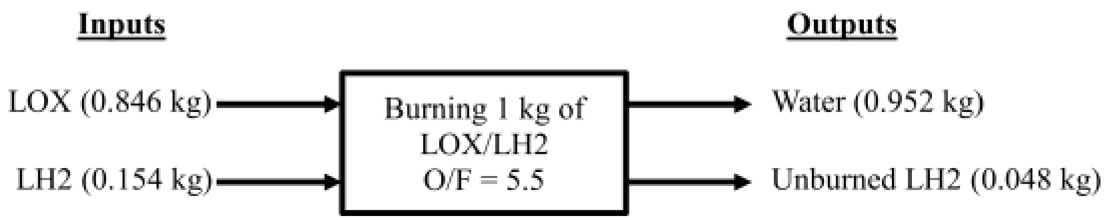


Figure 22: Mass flows associated with burning 1 kg of a LOX/LH2 propellant mixture with an O/F ratio of 5.5

The excess LH2 in the exhaust of a LOX/LH2 engine reacts with the local atmosphere in what is known as *afterburning*, meaning that the excess LH2 will combust and form water.

Burning of LOX/RP1 is a slightly more complicated reaction as the chemical formula for RP1 can only be approximated. However, exhaust products for this propellant combination can be found in (Kuzin 1997) who specifies the exhaust products of a Soyuz third stage. This stage uses the RD-0110 engine with an O/F of 2.2, which is close to the assumed 2.25 assumed in this research. The resulting LCI for burning of LOX/RP1 is shown in Figure 23. It is unclear whether (Kuzin 1997) includes afterburning. If afterburning is included in these emissions data, then some of the exhaust products are the result of excess fuel mixing and combusting with ambient air. The ambient air is not included in the LCI for the combustion of LOX/RP1, meaning that this is a potential source of some error. This can be addressed in future work where the fidelity of this model can be modified to improve fidelity by obtaining better data that is more representative of the process and is currently unavailable.

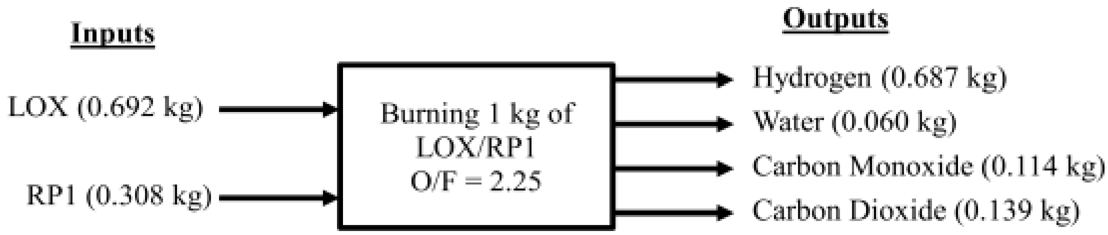


Figure 23: Mass flows associated with burning 1 kg of a LOX/RP1 propellant mixture with an O/F ratio of 2.25

The same literature (Kuzin 1997) provides the exhaust products for N2O4/UDMH. Combustion of 1 kg of this propellant combination is shown in Figure 24.

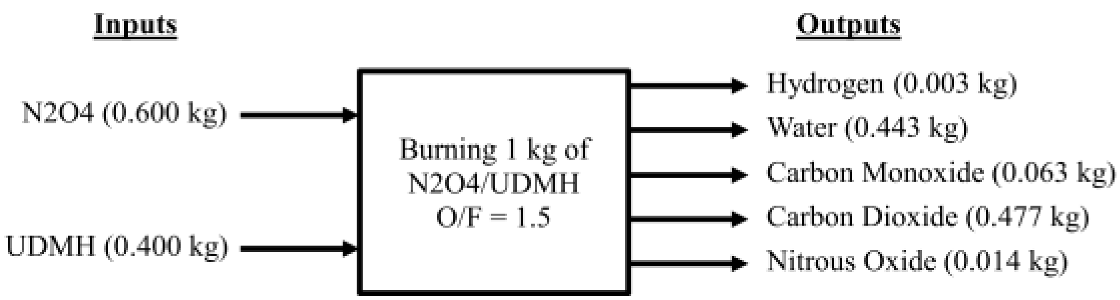


Figure 24: Mass flows associated with burning 1 kg of a N2O4/UDMH propellant mixture with an O/F ratio of 1.5

Finally, the combustion products for burning solid propellants were compiled from (Kuzin 1997). Literature specifically lists the solid boosters being assessed as being the SSSRB's, which use the same propellant mixture assumed in this research, making it an excellent fit to the system being assessed. The flows are given in Figure 25.

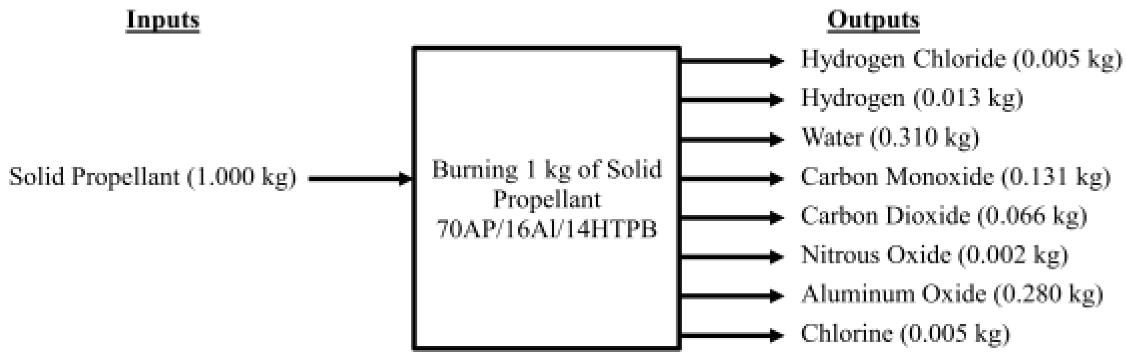


Figure 25: Mass flows associated with burning 1 kg of a solid propellant made up of 70% AP, 16% Al, 14% HTPB

In real world launches, some exhaust products are released into the land and water near the launch site early during launch, and some emissions are released above the atmosphere near the end of the final burn. It is assumed that all of the emissions are released into the atmosphere in this assessment. This assumption is made due to the complexity of rocket emissions interaction with the environment during launch. These interactions are further complicated by the variety in mission profile, which include launches from different locations, launch trajectories, type of launch pad, and other factors.

SimaPro (or any other LCA tool for that matter) is incapable of capturing all of the details associated with real world launches, so simplifications are necessary. These simplifications capture the general behavior of the rocket during launch and still allow the model to provide useful insights into the system. More complex modeling is beyond the scope of this assessment as this assessment is a fist attempt to modeling the general environmental behavior of a rocket. Accurately capturing impacts of burning propellants would require detailed modeling of the rocket's trajectory and flight path to determine the exact amount of exhaust produced and where it is emitted. Information would also have to be gathered about the local environment near the specific launch site and the atmosphere along the flight path. The results from this analysis may suggest whether or not more detailed modeling of use phase emissions will have an appreciable influence on the results of the LCA.

5.9 Comparison of Propellant Environmental Impacts

According to the analysis performed in SimaPro, it was found that producing different propellants had vastly different impacts on the environment. Figure 26 compares upstream burdens of producing 1 kg of these propellants. The contribution of each impact category is tabulated in Table 23 and Table 24.

It can be seen in this data that not only do total impacts change, but impacts by category. Production of LH2 and RP1 are most heavily influenced by the fossil depletion category. This category represents the consumption and depletion of non-renewable fossil fuels and is represented in (equivalent) barrels of oil. This makes sense as RP1 is derived from crude oil while LH2 is derived from either methane or naphtha.

The solid propellant, UDMH, and N2O4 are heavily influenced by the human toxicity impact category. Represented in terms of (equivalent) mass of dichlorobenzene released, human toxicity represents more long term effects and reflects the release of toxic chemicals into the environment. This category for these propellants is driven by their large consumption of ammonia during production. Solid propellant consumes ammonia during the production of ammonium perchlorate, UDMH consumes ammonia during both the production of dimethylamine and chloramine, while N2O4 is produced by the catalytic oxidation of ammonia.

The solid propellant, UDMH, and N2O4 also have large impacts in the fossil depletion and climate change categories. As before, fossil depletion represents the consumption of fossil fuels while climate change is given in terms of (equivalent) carbon dioxide production leading to global warming. Looking more closely into the inventory, these are the result of consuming fuels for both thermal and electrical energy production.

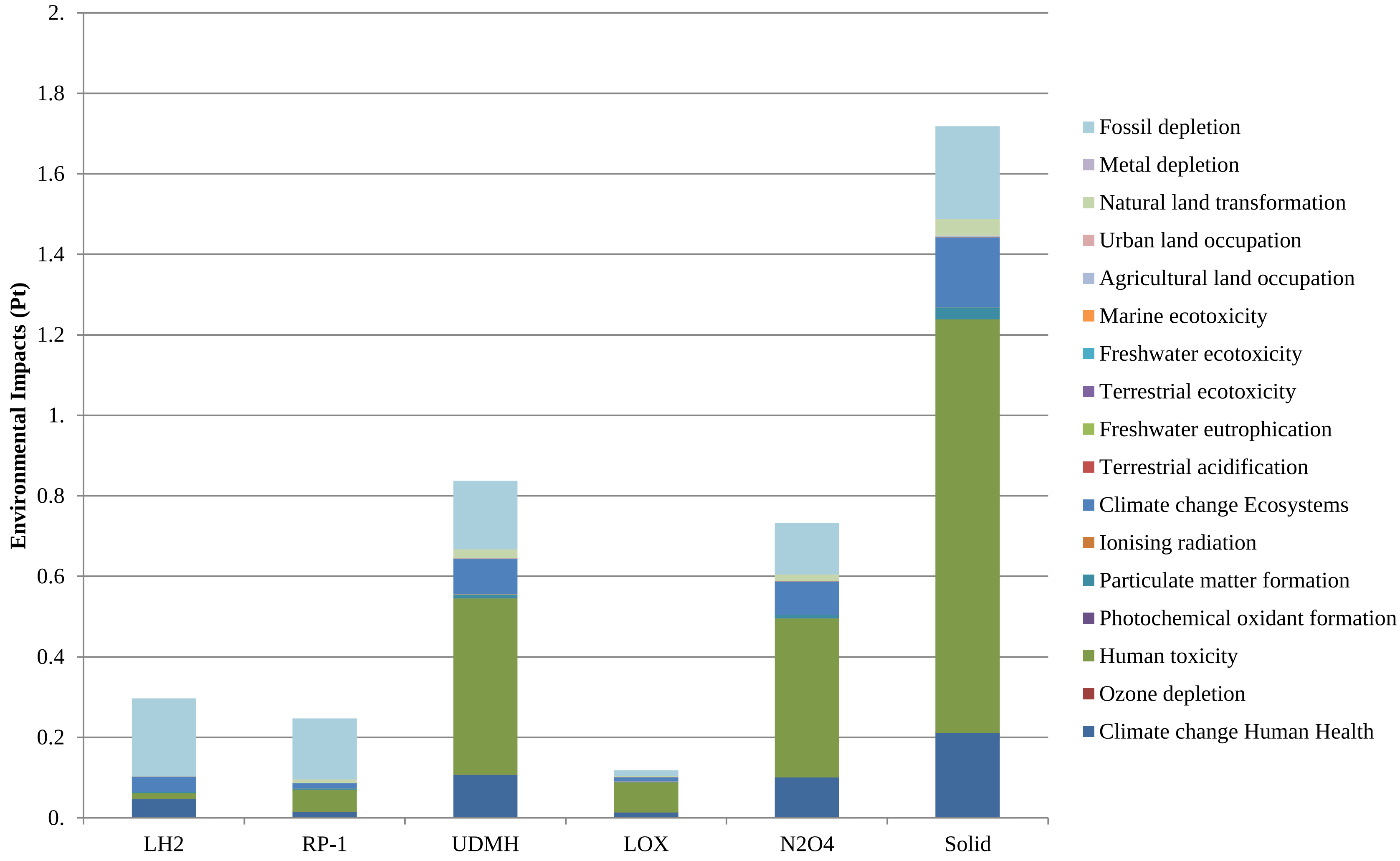


Figure 26: Comparing upstream impacts of producing 1 kg of the various rocket propellants under consideration, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Table 23: Contribution of each impact category while comparing upstream impacts (in Pts) of producing 1 kg of the various rocket propellants under consideration, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 1)

Propellant	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification	Freshwater eutrophication
LH2	4.65E-02	8.66E-08	1.47E-02	1.74E-06	3.00E-03	5.92E-06	3.80E-02	7.63E-05	4.02E-06
RP-1	1.53E-02	1.18E-05	5.42E-02	1.28E-06	3.60E-03	9.23E-06	1.25E-02	1.00E-04	5.33E-06
UDMH	1.07E-01	3.93E-05	4.39E-01	2.69E-06	1.00E-02	3.00E-04	8.71E-02	3.00E-04	1.00E-04
LOX	1.35E-02	4.87E-07	7.50E-02	3.25E-07	1.40E-03	5.14E-05	1.10E-02	3.84E-05	2.65E-05
N2O4	1.00E-01	6.92E-06	3.95E-01	2.28E-06	9.20E-03	2.00E-04	8.19E-02	2.00E-04	1.00E-04
Solid	2.12E-01	1.98E-05	1.03E+00	6.20E-06	2.94E-02	5.00E-04	1.73E-01	8.00E-04	3.00E-04

Table 24: Contribution of each impact category while comparing upstream impacts (in Pts) of producing 1 kg of the various rocket propellants under consideration, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 2)

Propellant	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
LH2	1.95E-05	4.60E-07	1.95E-06	2.37E-05	9.85E-06	5.00E-04	2.65E-06	1.94E-01
RP-1	1.00E-04	1.14E-06	4.43E-06	2.37E-05	1.00E-04	9.40E-03	6.07E-06	1.52E-01
UDMH	7.00E-04	1.27E-05	6.11E-05	9.00E-04	4.00E-04	2.18E-02	6.94E-05	1.70E-01
LOX	4.31E-05	2.23E-06	1.07E-05	8.85E-05	3.77E-05	2.50E-03	2.80E-06	1.42E-02
N2O4	6.00E-04	1.17E-05	5.84E-05	5.00E-04	3.00E-04	1.62E-02	3.32E-05	1.29E-01
Solid	1.20E-03	3.11E-05	1.00E-04	1.50E-03	7.00E-04	4.15E-02	4.00E-04	2.30E-01

When considering propulsion efficiencies, the propellants with the lowest average I_{sp} tend to have higher production impacts. A lower I_{sp} means that a relatively larger quantity (mass) of propellants is required to accelerate a particular payload by a desired ΔV. According to Figure 26, liquid propellants UDMH and N2O4, and the solid propellant have the highest upstream environmental impacts. Their impact is magnified since these propellants also have the lowest expected I_{sp} when compared to LOX/LH2 and LOX/RP1. Not only do these propellants have a higher impact, but more of those propellants are required.

During the use phase, impacts of burning propellants can be varied as different propellant combinations produce different combustion products and thus have different environmental impacts. The relative impacts of burning 1 kg of each propellant in the atmosphere is shown in Figure 27, and the contribution of each impact category is tabulated in Table 25 and Table 26.

As expected, the burning of LOX/LH2 had no impacts since only water vapor and some excess LH2 is released into the atmosphere. Burning LOX/RP1 and N2O4/UDMH releases large amounts of carbon dioxide, which is reflected in the results as a high climate change human health and climate change ecosystems. The N2O4/UDMH combination has a similar climate change impact as the LOX/RP1, but has its impacts increased beyond that of LOX/RP1 due to particulate matter formation and photochemical oxidant formation, which is due to the increased amounts of nitrogen oxides in the combustion products.

Burning of solid propellants had relatively high contributions from climate change human health and climate change ecosystems, which is due to the production of carbon dioxide. However, there the largest contribution comes from the human toxicity category. This is due to the release of chlorine and HCl during combustion. Surprisingly, ReCiPe did not score the solid propellant as having any impacts in the ozone depletion category, as was expected from literature. Closer inspection reveals that ReCiPe calculates ozone depletion based on emissions from ground-based sources and scores them in terms of equivalent amount of chloroflorocarbons (CFC's). The impact assessment method does not calculate ozone depletion potential as a result of chemical reaction due to exhaust products mixing directly with the ozone layer. In future work, this area ought to be addressed as it is expected that ozone depletion is an area where impacts of solid propellants are felt.

During disposal, it was found that disposal (land, atmosphere, and ocean) of LOX, LH2, and RP1 had little impact on the environment, while disposal of N2O4, UDMH, and solid propellants had a relatively larger impact. Nevertheless, these impacts were virtually negligible when compared to the life cycle of the rocket, so they were excluded from the analysis.

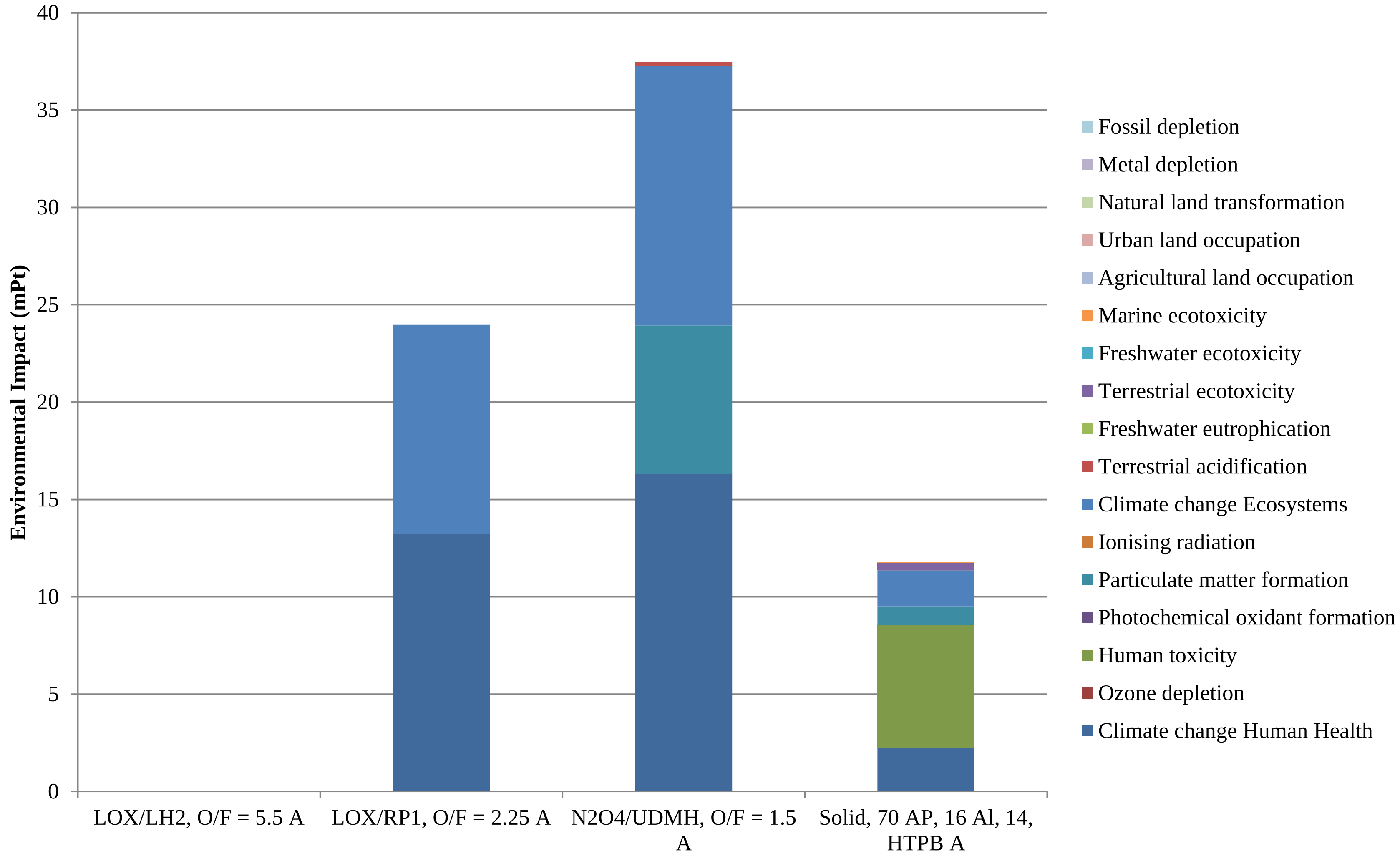


Figure 27: Comparing environmental impacts of burning 1 kg of each propellant in the atmosphere, using the ReCiPe 2008 Egalitarian Enpoint single score indicator

Table 25: Contribution of each impact category when comparing environmental impacts (in mPts) of burning 1 kg of each propellant in the atmosphere, using the ReCiPe 2008 Egalitarian Enpoint single score indicator (Part 1)

Propellant Combination	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification	Freshwater eutrophication
LOX/LH2, O/F = 5.5 A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LOX/RP1, O/F = 2.25 A	1.32E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.08E+01	0.00E+00	0.00E+00
N2O4/UDMH , O/F = 1.5 A	1.63E+01	0.00E+00	0.00E+00	5.20E-03	7.63E+00	0.00E+00	1.33E+01	2.07E-01	0.00E+00
Solid, 70 AP, 16 Al, 14, HTPB A	2.27E+00	0.00E+00	6.27E+00	7.00E-04	9.59E-01	0.00E+00	1.85E+00	2.60E-02	0.00E+00

Table 26: Contribution of each impact category when comparing environmental impacts (in mPts) of burning 1 kg of each propellant in the atmosphere, using the ReCiPe 2008 Egalitarian Enpoint single score indicator (Part 2)

Propellant Combination	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
LOX/LH2, O/F = 5.5 A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
LOX/RP1, O/F = 2.25 A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
N2O4/UDMH , O/F = 1.5 A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solid, 70 AP, 16 Al, 14, HTPB A	3.78E-01	2.12E-05	1.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

5.10 Chapter Summary

This chapter established the life cycle inventory for the six different propellants used by the different rocket configurations under consideration. For each propellant, the basic production process with typical inputs and outputs was described. Also for each propellant, the environmental burdens that can be expected during production were discussed.

It was found that the solid propellant had the highest environmental impacts both during production and while being burned. Of the liquid propellants, it was found that the N2O4/UDMH combination had the highest impacts both during production and burning. These were also the lowest efficiency propellants according to I_{sp}, meaning a larger quantity of these is required to launch 1 kg to LEO, compounding their impacts. It also suggests that these propellants stand to benefit the most from light-weighting.

The exact entries used are summarized in Table 27. The name of the entry is given if the inventory is found in the EcoInvent database. Those not found in predefined databases reference the exact inventory information in Appendix C that was input into SimaPro.

Table 27: Entries used for the life cycle inventory for each propellant

Propellant	Life Cycle Inventory Entry
Liquid Oxygen	Oxygen, liquid, at plant/RER S
Nitrogen Tetroxide	**Table C 7**
Liquid Hygrogen	Hydrogen, liquid, at plant/RER S
Rocket Propellant 1	Kerosene, at refinery/RER S
Unsymmetrical Dimethylhyrazine	**Table C 8**
Solid	**Table C 9**

6 LIFE CYCLE INVENTORY: STRUCTURAL MATERIALS AND MANUFACTURING

6.1 Summary of Chapter Contents

This chapter establishes the life cycle inventory for the structure of the rocket. This inventory covers harvesting and refining of materials used in structural components as well as manufacturing processes and techniques used to produce these components. These shall be used to define the inventory for the life cycle assessment model in SimaPro. It is necessary to define the various materials and manufacturing processes under consideration to ensure model transparency and traceability. This transparency and traceability is important since the purpose of this research is to determine whether a particular material substitution is better for the environment.

It is assumed that the structural materials described here, their harvesting and refining, and manufacturing processes are relatively well understood. Therefore, not as much time is spent detailing the life cycle inventory for each material in this chapter.

If an existing inventory can be used from a database, the specific entry used is given in each section while detailed inventory information can be found in Appendix C for those that require a manually created inventory. This chapter summary compiles all of the inventory entries in a single table (Table 32 on page 143), giving the exact name of each entry in the database, and the database identification number as it can be found in SimaPro.

The structural materials assumed in this chapter are those found in the baseline rocket, where no light-weighting is being considered. The life cycle inventory for the carbon fiber composites used in light-weighting is discussed in detail separately in Chapter 7 due to its more prominent role and importance to this research.

6.2 Structural Materials

6.2.1 Aluminum

Aluminum is a common material used in aerospace structures. It is assumed that aluminum and its alloys are well understood and the material harvesting and refining processes for the aluminum used in rockets is not appreciably different from aluminum consumed by other industries. Wrought aluminum alloys are commonly used in rocket applications. (Bruhn, Orlando et al. 1967) They have are currently found in many structures on the Falcon 9 (SpaceX 2009), Delta IV (United Launch Alliance 2007), and Atlas V (United Launch Alliance 2010), amongst other rockets.

From an LCA perspective, no distinctions are typically made on an alloy-by-alloy basis, so a general entry in the evoinvent database in SimaPro for wrought aluminum alloy is used.

The specific entry used for aluminum is "Aluminium, production mix, wrought alloy, at plant/RER S" found in the EcoInvent database.

6.2.2 Steel and Stainless Steel

As with aluminum, it is assumed that steels and stainless steels are fairly well understood materials. There are three different types of these steels assumed to be used in these rockets.

Steel is a useful material for solid motor cases.(Bruhn, Orlando et al. 1967; NASA 1970) Low alloy steel (D6AC) was used in both first stage Minuteman motor (Sutton and Biblarz 2001) and the Space Shuttle Solid Rocket Boosters (Riddle and Beckwith 1984). There are a number of LCI entries in different databases available through SimaPro, but the particular LCI entry for low alloy steel from the EcoInvent database is used.

Stainless steels are used in engine components and propellant feed lines. (Pratt & Whitney 1966) Stainless steels (or *chromium steels*) have a number of LCI entries in multiple databases in SimaPro. The LCI for chromium steel in the EcoInvent database is used for this material.

The high alloy steel A-286 is an iron-based super alloy of steel that contains large fractions of nickel and chromium (Granta 2012) and is used in a number of engine components and high stress structures (Pratt & Whitney 1966; Huzel and Huang 1992). An LCI was found in the EcoInvent database for an iron-nickel-chromium alloy of steel called Inconel, which is slightly different from A-286 steel, but is similar enough for the purposes of this LCA.

The exact entry for low alloy steel is named "Steel, low-alloyed, at plant/RER S," while "Steel, electric, chromium steel 18/8, at plant/RER S" is used for stainless steel, and "Iron-nickel-chromium alloy, at plant/RER S" is used for the high alloy steel, each found in the EcoInvent database.

6.2.3 Titanium

Titanium is used for small, high strength components like the Space Shuttle Main Engines gimbal (Rocketdyne 1998) and the RCS propellant tanks on the Falcon 9 rocket (SpaceX 2012). Surprisingly, there were no LCI entries in any of the database entries found in SimaPro. Therefore, an LCI needed to be constructed from literature. An LCI for titanium was assembled from (Norgate, Rajakumar et al. 2004). The paper outlines several common titanium production techniques. Based on information in the article, it is assumed that the Kroll Process is selected here as the most likely way titanium for aerospace applications is made. The basic production process for production of titanium through the Kroll process is described below.

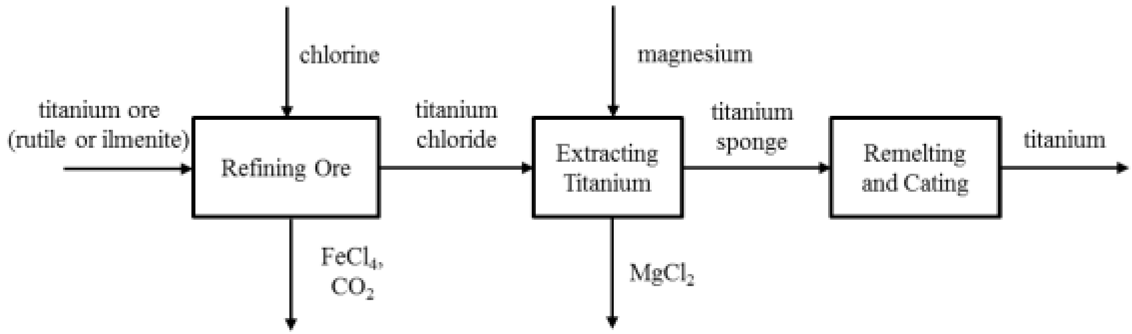


Figure 28: Graphical representation of titanium production

Values for energy consumption, emissions, and other environmental burdens produced by this process are found in (Norgate, Rajakumar et al. 2004) as well and were used in the construction of the LCI for titanium. A new entry was created in SimaPro to represent the production of titanium according to the literature and process described above, and the basic flows are shown in Figure 29. The exact inputs as entered into SimaPro are found in Appendix C.

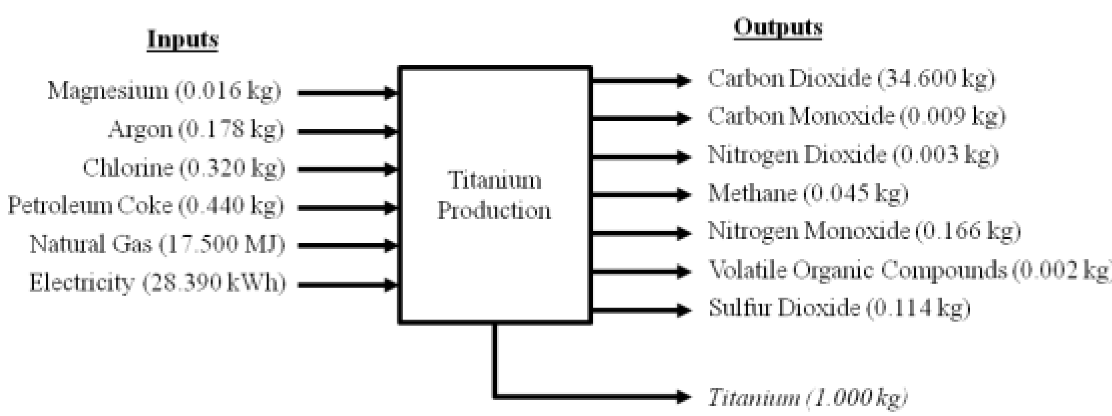


Figure 29: Production of 1 kg of titanium using Kroll Process

6.2.4 More Exotic Metals

Virtually pure molybdenum is used in the combustion chamber of RCS thrusters. (Taeber and Weary 1973) The predefined LCI for pure molybdenum found in the EcoInvent database was used to represent this material. The entry used is named "Molybdenum, at regional storage/RER S" and is found in the EcoInvent database.

Cobalt alloy is also used in RCS thrusters, primarily for the bell or skirt of the thruster. (Taeber and Weary 1973) As with molybdenum, a suitable LCI for cobalt was found in the econinvent database. The entry used is named "Cobalt, at plant/GLO S" and is found in the EcoInvent database.

6.2.5 Polymers, Ceramic, and Graphite

According to (NASA 2004), the insulation on the Space Shuttle External Tank is a rigid, polyurethane foam that is either sprayed into place or is adhered onto the side of the tank as tiles, depending on the location. In accordance with this, it is assumed that polyurethane foam is used to insulate cryogenic propellant tanks on the rockets sized here. An entry for polyurethane foam exists in the EcoInvent database and is used in the SimaPro model. The entry is named "Polyurethane, rigid foam, at plant/RER S" and is found in the EcoInvent database.

According to both (Humble, Henry et al. 1995) and (Sutton and Biblarz 2001), EPDM is used as an insulator between the solid propellant grain and the motor casing. This is assumed to be the case for the solid rockets in this assessment. No exact entry is found for EPDM in SimaPro’s databases, but it is approximated with an EcoInvent database entry for synthetic rubber. The exact entry in the EcoInvent database is named "Synthetic rubber, at plant/RER S.”

Epoxy is used as a matrix material in the carbon fiber composites used for light-weighting. This material is described in further detail in Chapter 7 (starting on page 144) as part of the composite structure.

The base heat shield of the rocket must be an insulator capable of higher temperatures than the other insulators discussed thus far. According to (NASA 1988), the Space Shuttle uses thermal tiles made of 99.9% pure silica and the tiles have a density of roughly 140 kg/m^3. EcoInvent contains an entry for foam glass with similar properties, but it is unclear whether the entry is intended as a high temperature insulator. Nevertheless, it is assumed to represent the material used for the base heat shield well enough. The exact entry is named "Foam glass, at plant/RER S." Though glass is not exactly the same as the silica used in rocket insulation, structures made from this material are relatively small with a low mass, contributing little to the overall lifetime environmental impacts.

Graphite and carbon-carbon composites are frequently used in solid motor casing nozzles (Bruhn, Orlando et al. 1967; Humble, Henry et al. 1995; Sutton and Biblarz 2001) due to their high resistance to heat. These nozzles are typically ablative, meaning that temperature of the material is controlled by allowing it to vaporize or wear away. No exact entry is found for such a material in SimaPro's databases, but an entry for graphite can be used as an approximation. This entry is named "Graphite, at plant/RER S."

6.2.6 Relative Impacts of Using Different Structural Materials

The material harvesting and refinement phase has different impacts on the environment, depending on the material being considered. Differences include how the material is mined or produced, how it is purified, how it is refined into its final form, and so on. Certain materials have significantly higher environmental impacts during harvesting and refinement than other materials. This is important to note since the impacts of a small quantities of one particular material can greatly overshadow the impacts of another material that perhaps makes up a larger portion of the rocket's structural mass, making the results of the impact assessment more sensitive to uncertainty and errors with that particular material.

Figure 30 shows the relative environmental impacts for 1 kg of each of the different materials used in the structure of the rocket. These results are based on the single score, long term impacts for each material, though individual impact categories are shown. Numerical results are tabulated in Table 28 and Table 29. Note that some categories experience minimal to negligible impacts.

It can be seen that harvesting of commonly used metals like aluminum, low alloy steel, and stainless steel, has relatively low environmental impacts. On the other hand, metals like the titanium, iron-nickel-chromium steel, and cobalt have significantly higher environmental impacts during harvesting, while molybdenum has extremely high impacts.

This is important because it suggests that consumption of large amounts of one metal may not matter as much (from and environmental perspective) as consuming small quantities of another metal. This indicates that even though certain materials are consumed in small quantities, they can be just as important, if not more important to study than other materials.

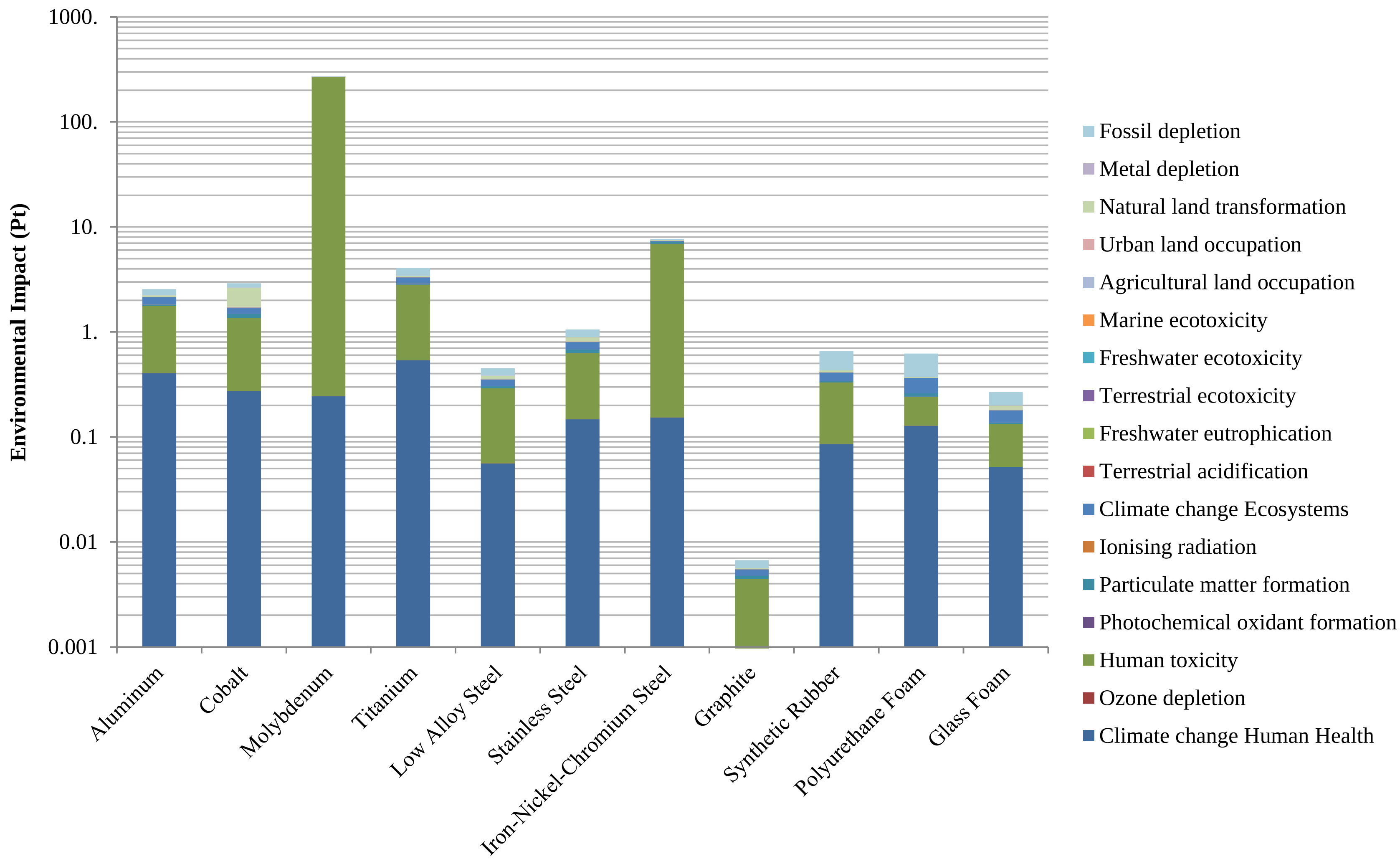


Figure 30: Comparing environmental impacts for 1 kg of different materials used in the rocket's structure, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Table 28: Contribution of each impact category when comparing environmental impacts (in Pts) for 1 kg of different materials used in the rocket's structure, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 1)

Material	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification	Freshwater eutrophication
Aluminum	4.03E-01	1.70E-05	1.36E+00	1.05E-05	5.61E-02	5.00E-04	3.29E-01	1.00E-03	3.00E-04
Cobalt	2.74E-01	1.54E-05	1.08E+00	3.79E-05	1.25E-01	5.00E-04	2.24E-01	2.30E-03	3.00E-04
Molybdenum	2.44E-01	1.15E-05	2.67E+02	6.31E-05	5.46E-01	4.00E-04	2.00E-01	4.30E-03	3.27E-02
Titanium	5.39E-01	4.39E-05	2.29E+00	1.24E-05	4.88E-02	1.80E-03	4.40E-01	1.40E-03	8.00E-04
Low Alloy Steel	5.58E-02	1.91E-06	2.35E-01	2.26E-06	1.57E-02	4.64E-05	4.56E-02	1.00E-04	7.17E-05
Stainless Steel	1.47E-01	6.06E-06	4.77E-01	5.80E-06	5.53E-02	1.00E-04	1.21E-01	5.00E-04	1.00E-04
Iron-Nickel-Chromium Steel	1.53E-01	8.97E-06	6.77E+00	2.61E-05	3.03E-01	2.00E-04	1.25E-01	1.01E-02	9.00E-04
Graphite	9.00E-04	5.42E-08	3.50E-03	4.00E-08	3.00E-04	2.23E-06	8.00E-04	3.15E-06	1.18E-06
Synthetic Rubber	8.55E-02	1.65E-05	2.45E-01	3.63E-06	8.90E-03	9.93E-05	6.99E-02	2.00E-04	6.09E-05
Polyurethane Foam	1.28E-01	5.58E-07	1.14E-01	5.86E-06	1.79E-02	3.26E-05	1.05E-01	4.00E-04	3.79E-05
Glass Foam	5.18E-02	4.39E-06	8.09E-02	1.52E-06	3.80E-03	2.00E-04	4.24E-02	9.16E-05	1.74E-05

Table 29: Contribution of each impact category when comparing environmental impacts (in Pts) for 1 kg of different materials used in the rocket's structure, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 2)

Material	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
Aluminum	3.30E-03	4.75E-05	2.00E-04	1.90E-03	1.50E-03	7.54E-02	3.00E-04	3.29E-01
Cobalt	1.20E-03	2.78E-05	1.00E-04	6.10E-03	2.28E-02	9.13E-01	1.00E-03	2.64E-01
Molybdenum	1.61E-02	3.90E-03	2.16E-02	7.80E-03	3.93E-02	1.32E+00	2.46E-01	2.60E-01
Titanium	1.20E-03	6.79E-05	3.00E-04	4.70E-03	1.50E-03	1.00E-01	7.49E-05	6.40E-01
Low Alloy Steel	7.00E-04	1.92E-05	7.52E-05	7.00E-04	5.00E-04	2.86E-02	1.60E-03	6.71E-02
Stainless Steel	3.20E-03	1.00E-04	5.00E-04	1.90E-03	2.00E-03	7.86E-02	7.30E-03	1.61E-01
Iron-Nickel-Chromium Steel	8.90E-03	2.00E-04	1.00E-03	2.40E-03	3.00E-03	1.56E-01	6.60E-03	1.53E-01
Graphite	8.54E-06	1.06E-07	5.05E-07	4.44E-06	4.73E-06	1.00E-04	7.42E-07	1.00E-03
Synthetic Rubber	3.00E-04	6.75E-06	3.05E-05	2.10E-03	3.00E-04	1.65E-02	7.95E-05	2.32E-01
Polyurethane Foam	3.00E-04	1.10E-05	1.58E-05	2.00E-04	9.58E-05	4.80E-03	3.32E-05	2.52E-01
Glass Foam	1.00E-04	2.26E-06	1.08E-05	2.60E-03	2.00E-04	1.63E-02	7.00E-04	6.89E-02

6.3 Manufacturing Processes

6.3.1 Metalworking Processes

6.3.1.1 Sheet Metal Forming

Sheet metal forming includes operations like rolling, bending, stamping, and spinning of sheets of metal into the desired shape. Sheet metal processes are likely the most widely used processes on a rocket. These processes are useful for making large and relatively simple structures.

Propellant tanks, requiring large empty volumes, take advantage of monocoque sheet metal structures. Both older rockets, like the Saturn V (Bruhn, Orlando et al. 1967), and more recent rockets, like North Korea's Unha-3 (Wright 2012) use such structures in their main propellant tanks. Sheet metal spinning processes are also used in smaller propellant tanks, like the RCS propellant tanks used on the Falcon 9. (SpaceX 2012)

Payload fairings, apart from the propellant tanks themselves, are also some of the largest components on a rocket in terms of dimensions. Monocoque skin and stringer structures are used in many modern rockets, like the Delta II (The Boeing Company 2006) and the Atlas V (United Launch Alliance 2010). Nose cones for the payload fairing on the Japanese H-IIA are made by spinning of large sheets of metal. (Trends in Japan undated)

Sheet metal components are also found in many (though much smaller) parts in engine components. (Pratt & Whitney 1966) Structures like light-duty housings, shields, and covers can be made using stamping operations, while metal gaskets can be made blanked from thin sheets of metal.

6.3.1.2 Casting

Casting is a good near-net-shape process that can form metal into thicker and more complex shapes than sheet metal forming. Such processes are found more commonly in smaller parts and components, such as those found in the engines. (Pratt & Whitney 1966) These include structures like heavier duty housings and covers used for pumps and valves.

6.3.1.3 Forging

Of the 43 key parts identified on the RL-10 engine, 16 components were primarily formed using forging processes. (Pratt & Whitney 1966) These components include gimbal parts, pump housings, impellers, rotors, and valves. Forging metal, as opposed to casting, can yield parts of considerably higher strength because the forging process yields a more mechanically advantageous grain structure in the metal. (Kalpakjian and Schmid 2003)

6.3.1.4 Extruding Tubes, Wires, and Bars

Tubes, wires, and bars can each be made using extrusion processes, though additional bending and cutting may be required to form them into their final shape. Extrusion has the advantage of being able to form high aspect ratio shapes with a constant cross section. These cross sections can be simple shapes, or can be more complex structural designs. Extruding can also create hollow shapes, which would be difficult with forging or casting.

Tubing is primarily used in propellant and pressurant feed lines. However, tubing can also be used for some structural components. For instance, payload attachment fittings used on the Detla II, Delta IV, and Atlas V make use of metal tubing for structural support. (The Boeing Company 2006; United Launch Alliance 2007; United Launch Alliance 2010) Bars and tubing can also be used in larger structural components, like the inter-stages on the Proton and Soyuz rockets. (Ariane Space 2006; International Launch Services 2009)

Metal bars can be found in engine components, such as valves, gimbal components, and other smaller, miscellaneous parts. (Pratt & Whitney 1966)

Wires are necessary for any electrical system, but can also be used in smaller components like springs.

6.3.1.5 Machining

Machining, or the shaping of material through chip formation, is useful for producing complex, precision components. In many cases, machining is not used for the primary shaping of a part but is used to finish a part that had previously been cast, forged, extruded, or formed in a sheet metal process. It can be expected that most components on a rocket require some machining.

Machining, however, is emerging as the primary process in producing certain large structures. For instance, the Delta II propellant tanks are made of large metal plates with an isogrid pattern machined into them. These plates are then bent to the correct shape. (Proctor 2002) Machining such a large structure can lead to excessive waste, but the performance of the component is far superior to that of a traditional skin and stringer structure.

6.3.1.6 Joining

Screws, nuts, and bolts are used to mechanically fasten a variety of component. However, welding is the preferred method for joining critical components. Welding offers a strong, continuous bond between two metals. For the strength, welding also provides a lighter joint than other mechanical fasteners. (Kalpakjian and Schmid 2003)

Friction stir welding is used in manufacture of propellant tanks (SpaceX 2012), engine components like bells (Astrium 2003) and combustion chambers (Russell and Carter 2007), and any number of other components that require a strong bond.

6.3.1.7 Approximating Metalworking in SimaPro

Databases in SimaPro contain many entries for specific metal manufacturing processes. These vary from theoretical data to real world industry data. However, even when the rocket is simplified into a manageable number of components, each component can require many different manufacturing processes to produce. Fortunately, the databases accessed by SimaPro offer a good solution. There are multiple database entries in EcoInvent that represent a general metalworking manufacturing process. These inventories include a variety of commonly found processes from industry, and factor in elements like production of waste. All inputs and outputs are based on a process that is required to produce a 1 kg part of a particular metal. Since a variety of metalworking processes are included, there is no need to specify exactly which processes were used in every component. The exact manufacturing processes used for each material are defined in Table 32 in this chapter's summary.

In the future, it is possible to refine and add detail to this part of the life cycle model. For the purposes of this LCA, these generalized manufacturing processes give a good approximation of environmental impacts due to manufacturing of parts.

6.3.2 Other Manufacturing Processes

During manufacturing and assembly, this LCA focuses on metal and composite structures. Structures made with other materials, such as polymers, ceramics, and graphite, represent a small fraction of the total rocket mass. As observed from database entries for other materials in literature and in SimaPro's databases, manufacturing impacts are roughly proportional to the size of the component being produced. Therefore, it is assumed that manufacturing impacts of non-metal, non-CFRP are negligible and they are excluded from this LCA.

6.3.3 Relative Impacts of Using Different Manufacturing Techniques

Figure 31 compares the environmental impacts of different manufacturing process. It is assumed each process represents the burdens associated with producing a typical 1 kg part out of the indicated material. These processes are generalized processes based on mixed production from industry and they include most of the common metalworking processes described in the previous sections.

It can be seen that manufacturing processes for aluminum are higher than that of steel and stainless steel. However, general metal manufacturing is about 50% worse than aluminum manufacturing. Since not every metal found in the rocket's structure has a database entry in SimaPro, use of the general metal manufacturing process entry shown above fits well with the worst-case scenario assumption. Though it is possible that manufacturing certain parts out of certain materials not shown here may be even worse for the environment than the general manufacturing process, using this entry at least pushes the results in the correct direction and accounts for some of the potential impacts.

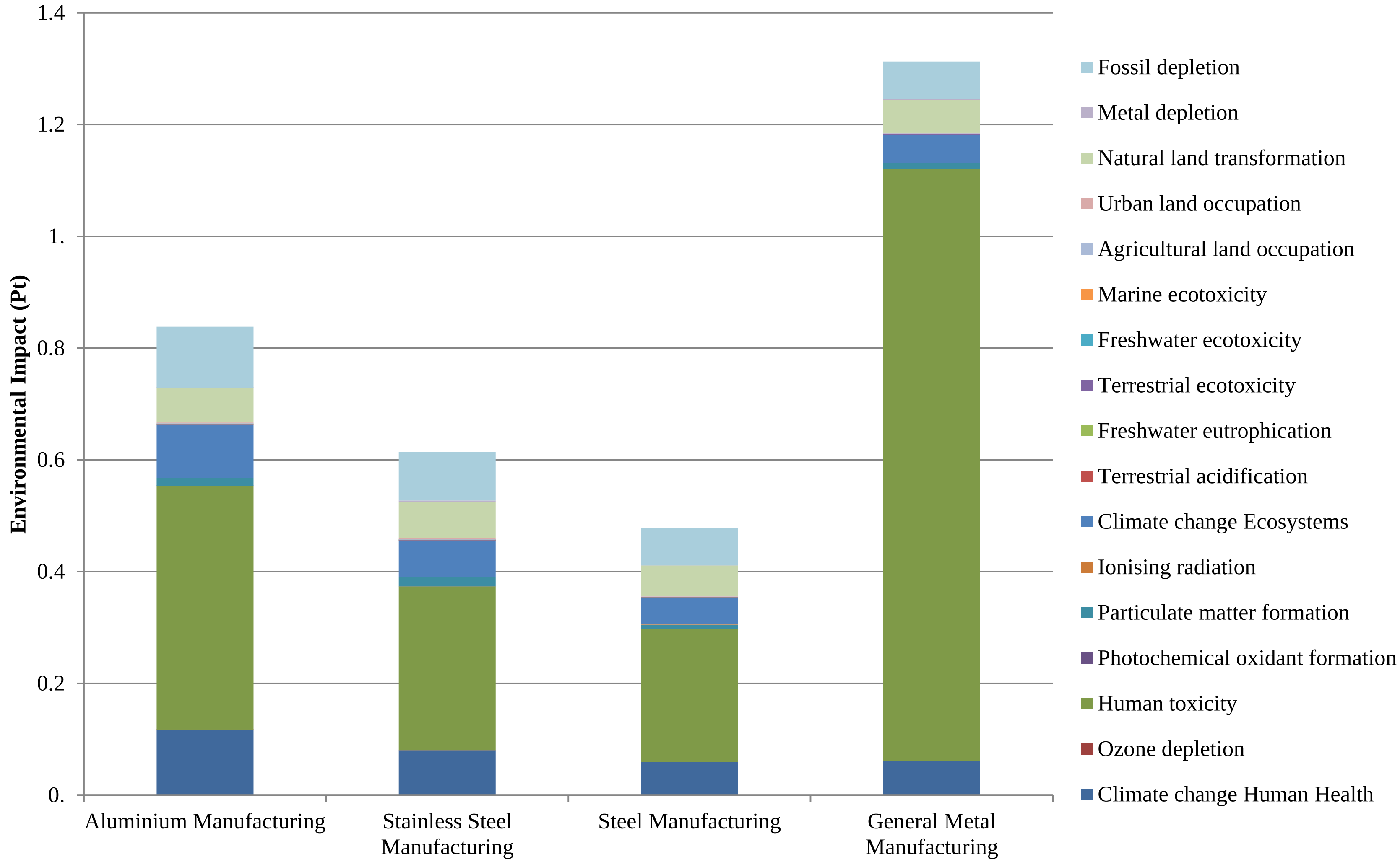


Figure 31: Comparing environmental impacts for producing a 1 kg part using a particular material, using the single score indicator according to the ReCiPe 2008 Egalitarian Endpoint impact assessment method

Table 30: Contributions of each impact category when omparing environmental impacts (in Pts) for producing a 1 kg part using a particular material, using the single score indicator according to the ReCiPe 2008 Egalitarian Endpoint impact assessment method (Part 1)

Type of Manufacturing	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification	Freshwater eutrophication
Aluminium Manufacturing	1.17E-01	6.15E-06	4.37E-01	2.87E-06	1.35E-02	2.00E-04	9.58E-02	3.00E-04	1.00E-04
Stainless Steel Manufacturing	8.00E-02	4.48E-06	2.94E-01	2.35E-06	1.62E-02	1.00E-04	6.54E-02	2.00E-04	8.74E-05
Steel Manufacturing	5.93E-02	3.54E-06	2.39E-01	1.54E-06	7.30E-03	1.00E-04	4.84E-02	1.00E-04	7.14E-05
General Metal Manufacturing	6.17E-02	3.69E-06	1.06E+00	1.89E-06	1.04E-02	1.00E-04	5.04E-02	2.00E-04	2.00E-04

Table 31: Contributions of each impact category when omparing environmental impacts (in Pts) for producing a 1 kg part using a particular material, using the single score indicator according to the ReCiPe 2008 Egalitarian Endpoint impact assessment method (Part 2)

Type of Manufacturing	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
Aluminium Manufacturing	1.00E-03	1.43E-05	6.73E-05	8.00E-04	1.00E-03	6.25E-02	7.87E-05	1.09E-01
Stainless Steel Manufacturing	1.20E-03	3.61E-05	1.00E-04	9.00E-04	1.20E-03	6.60E-02	1.70E-03	8.72E-02
Steel Manufacturing	6.00E-04	1.02E-05	4.31E-05	7.00E-04	9.00E-04	5.47E-02	4.00E-04	6.59E-02
General Metal Manufacturing	1.40E-03	2.23E-05	1.00E-04	7.00E-04	1.00E-03	5.90E-02	8.00E-04	6.77E-02

The largest contributor to the environmental impact resulting from metalworking processes is in human toxicity. This is the result of lubricants and coolants being consumed as well as the use of chemicals for metal treatment and cleaning processes. Other large contributors are climate change categories and fossil depletion. These are the result of the production of energy consumed during these processes, including the consumption of fuels and the emission of carbon dioxide into the atmosphere.

It is expected that steel manufacturing would have a higher impact than aluminum as it takes more energy to cut (GRANTA 2012). However, these database entries include scrap and waste produced during the process. Aluminum has higher upstream impacts, so producing aluminum scrap and waste drives up the manufacturing impacts. The notion of "buy-to-fly" ration roughly represents the amount of scrap produced by giving a ratio comparing the amount of a material initially purchased to the amount that eventually ends up in the final product. This ratio is heavily dependent on the type of manufacturing process being used and the initial form of the material (ingot, sheet, bar, etc.).

A typical buy-to-fly ratios for a machined metal component is 15:1 (Lenger 2011), but streamlined rocket manufacturing processes claim a buy-to-fly ratio of as low as 1.1:1 (Anderson 2012). By comparison, CFRP components have typical buy-to-fly ratios of about 2:1 (Lenger 2011). The buy-to-fly ratio is represented in the existing EcoInvent database entries on general manufacturing processes. These processes include industry average waste production for typical metal processes. A 2:1 buy-to-fly ratio is assumed for CFRP's, included as a kg waste of CFRP produced for each kg found in a CFRP component.

6.4 The Relative Significance of Manufacturing Processes

Based on the inventory entries in databases in SimaPro, it was found that manufacturing a 1 kg component out of a particular material always had a lower environmental impact than harvesting and refining 1 kg of that material. This is true even though the inventories for the manufacturing processes included waste and excess material. The conclusion was confirmed by looking at life cycle analyses in literature, specifically (The Japan Carbon Fiber Manufacturers' Association 2008) where the life cycles of an automobile and an airplane were assessed.

Manufacturing processes typically do not contribute significantly to the life cycle impacts of a system, though they do have a non-negligible contribution. It is important that *some* account is taken to include manufacturing processes, but literature does not suggest that the results of the LCA will change significantly if higher fidelity representation of the manufacturing process occurs.

During the analysis, it was found that manufacturing processes, as defined here, did not end up representing a significant part of the rocket's life cycle. Even while assuming some error in the inputs, it was not found that the results from the impact assessment would change such that the conclusions were challenged or invalidated. For this reason, it is determined that approximating specific manufacturing operations with a generalized manufacturing process is acceptable for the purposes of this LCA.

6.5 Chapter Summary

This chapter first summarized the different materials used in structural components of the rocket. A comparison was made of the relative environmental impacts of harvesting 1 kg of each material, showing that certain materials have a significantly higher embodied environmental cost. This high cost can make the LCA more sensitive to certain materials, even though they are found in small quantities on the rocket.

Next, this chapter discussed different manufacturing processes used to produce different components. Even though the rocket has been simplified and components were generalized, many different manufacturing processes could still be required. A comparison was done on the impacts of different manufacturing processes and it was found that using a generalized process for a particular material would be adequate for the purposes of this LCA.

The exact entries used in the LCI for structural materials are summarized in Table 32. Entries found in the EcoInvent database are named while the exact inputs used entered manually into SimaPro are referenced in Appendix C.

Table 32: Summary of harvesting/refining and manufacturing entries used in the life cycle inventory of structural materials

Material	Harvesting and Refining Entry	Manufacturing Entry
Aluminum (Wrought)	Aluminium, production mix, wrought alloy, at plant/RER S	Aluminium product manufacturing, average metal working/RER S
Low Alloy Steel	Steel, low-alloyed, at plant/RER S	Steel product manufacturing, average metal working/RER S
Stainless Steel	Steel, electric, chromium steel 18/8, at plant/RER S	Chromium steel product manufacturing, average metal working/RER S
Iron-Nickle-Chromium Steel	Iron-nickel-chromium alloy, at plant/RER S	Steel product manufacturing, average metal working/RER S
Titanium	**Table C 6**	Metal product manufacturing, average metal working/RER S
Cobalt	Cobalt, at plant/GLO S	Metal product manufacturing, average metal working/RER S
Molybdenum	Molybdenum, at regional storage/RER S	Metal product manufacturing, average metal working/RER S
Carbon Fiber Reinforced Polymer	**Table C 3**	**Table C 5**
Polyurethane Foam	Polyurethane, rigid foam, at plant/RER S	*neglected*
Synthetic Rubber	Synthetic rubber, at plant/RER S	*neglected*
Glass Foam	Foam glass, at plant/RER S	*neglected*
Graphite	Graphite, at plant/RER S	*neglected*
Explosive	Explosives, tovex, at plant/CH S	*neglected*

7 LIFE CYCLE INVENTORY: CARBON FIBER REINFORCED POLYMER

7.1 Overview of Chapter Contents

Carbon fiber composites play a prominent role in this analysis. Since it is known that carbon fiber composites typically have higher embodied burdens than metals they are replacing during light weighting, the fundamental issue while determining if light-weighting is environmentally preferable is seeing if upstream burdens are outweighed by benefits downstream in the product's life. However, as identified in the Literature Review, there is great uncertainty as to the upstream environmental burdens associated specifically with carbon fiber production.

Due to the importance of carbon fibers in this analysis, the life cycle inventory for carbon fibers and their composites is examined in much more detail than other structural materials. This chapter begins by describing the basic carbon fiber production process. Next, this chapter develops a parametric carbon fiber production model that is capable of calculating information needed for the life cycle inventory. Parameters that are representative of the type of carbon fibers that are used in aerospace are used to calculate case specific results. These results define the life cycle inventory for carbon fibers.

This chapter ends by discussing the composite structure. This includes a discussion of the matrix material used and the manufacturing processes assumed used to produce the light-weighted components of the rocket.

7.2 Purpose of Carbon Fiber Production Model

Information about the production of carbon fibers is required to construct a more detailed life cycle inventory than what is currently available from any single source. The information required goes beyond simply identifying the embodied energy and carbon dioxide of some generic process. It must be verified that embodied energy and carbon dioxide data is representative of the *particular* carbon fiber type that is being considered. Furthermore, additional resource inputs and waste outputs to the process must be identified and quantified.

It is important to identify and include these additional resources and byproducts in the life cycle inventory. Literature (GRANTA 2012) suggests that carbon fibers can have a higher environmental impact during production than the metals they are typically used to replace. Assembling an inventory that is as representative of the particular carbon fibers being considered helps ensure that the added upstream burdens are well understood and that any potential downstream benefits actually outweigh these burdens.

The issue is assembling a more complete inventory as one is not available in literature or any databases. Data can be gathered from real world processes, but real world carbon fiber production can contain many steps, and the specific process and parameters can change from manufacturer to manufacturer. It is difficult to obtain detailed, case-specific inventory information about a particular type of carbon fiber due to proprietary issues and that the particular process of interest is not always accessible for manual data gathering.

This issue is addressed by developing a carbon fiber production model. The real world process is generalized as a series of primary steps that are necessary (according to chemistry) in all carbon fiber production processes. A series of secondary steps are used to capture auxiliary processes. These generalized steps are assembled in such a way that they can represent any typical real world process, facilitating analysis and helping determine case-specific quantities.

This representation of real world processes can be used analytically to perform deterministic calculations. The way in which the process is broken down allows for each step to be assessed independently as an open system where resources and energy flow in, and modified fibers and waste flow out. Assuming or given some known parameters about each step, unknown inputs and outputs can be determined *qualitatively* using a chemical balance and *quantitatively* using thermodynamic conservation equations.

The particular model described here represents a real world carbon fiber production process as a series of three primary steps: stabilization, carbonization, and graphitization. Three secondary or auxiliary steps are also included to represent processes like stretching, cooling, spooling, and so on. These processes and their corresponding input and output flows are organized according to a flow chart that was developed to represent the real world flow of resources, waste, and energy through each step. Some basic, case-specific parameters of the particular process of interest are gathered from literature and unknown quantities are calculated by solving a mass and energy conservation equation. These results are used to assemble a life cycle inventory for the carbon fibers under consideration in this research.

7.3 Overview of Fiber Production

The basic carbon fiber production process is shown graphically in Figure 32.

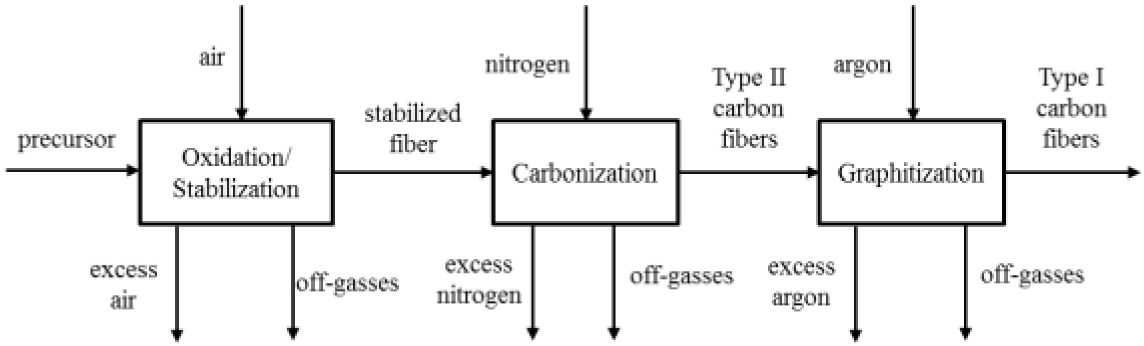


Figure 32: Representation of carbon fiber production

Carbon fibers are made through pyrolysis of a carbon-rich precursor material such as pitch, cellulose, rayon, and (most commonly) polyacrylonitrile (PAN). The precursor is first oxidized at elevated temperatures (180-300°C) to stabilize the material. Stabilization typically occurs on air while the fibers are under tension to maintain desired molecular orientation. The fibers are then heated at high temperatures (up to 1700° C) in a process called *carbonization* to remove non-carbon atoms from the precursor. Carbonization is performed in an inert environment, using a gas such as nitrogen. After carbonization, what are known as Type II carbon fibers is prepared, having a carbon content of approximately 92% and favoring higher tensile strength. An additional, optional step called *graphitization* may occur at still higher temperatures (up to 2800° C) in an inert environment using a gas like argon, since nitrogen would no longer be inert at such temperatures. After graphitization, Type I fibers are prepared, having a carbon content close to 100% and favoring higher tensile modulus. (Donnet and Bansal 1990; Peebles 1995)

The precursor used, process temperatures, and some other parameters determine the mechanical properties of the material. The fibers most likely used in aerospace structures are known as *intermediate modulus* (IM) fibers. (Toray Carbon Fibers 2008) These fibers have a tensile strength of approximately 5.5-7.0 GPa, a tensile modulus approximately between 275-300 GPa, and a density of roughly 1790 kg/m^3. (Hexcel undated) Intermediate modulus fibers are typically made from a PAN precursor and undergo a carbonization process but not a graphitization process. (Morgan 2005) Properties are only approximate as different manufacturers produce slightly different variations of the fibers, depending on the precursor and the specific process used.

In order to mitigate issues identified in the Literature Review with determining upstream environmental burdens, a more detailed carbon fiber production model is developed and described in the following sections. Parameters that are found to most closely reflect the production of IM fibers used in aerospace applications are plugged into this model to complete the LCI for the fibers. The results from this model were used to construct the upstream LCI for the fibers.

7.4 The Carbon Fiber Production Model

7.4.1 Purpose of the Model

The purpose of the carbon fiber production model is to provide a transparent, flexible, and adaptable tool to calculating case-specific information about the production of carbon fiber. It is used in this dissertation to clearly show how the life cycle inventory for carbon fibers was established. This is necessary because of the large uncertainty identified in the Literature Review (Chapter 2) as to the environmental burdens of carbon fiber production and due to the prominent role carbon fibers play in the light-weighting of rockets.

The model can be used in two ways. First, known parameters can be used to calculate unknown values on a case-by-case basis. This addresses the multiple issues in published literature identified in the Literature Review by allowing the analyst to plug in personalized data and perform tailored and more meaningful calculations. These issues are reiterated below.

- Large range of published values, addressed by providing a means of obtaining case-specific results
- Data richness and diversity, addressed by organizing and quantifying inputs and outputs to the production process and allowing case-specific data to be added to increase fidelity
- No distinction amongst different carbon fiber types, addressed by allowing parameters in the model to be changed to reflect the production of different types of carbon fiber

Secondly, an analyst may start with published information on environmental burdens and use the model as a framework to back-track what assumptions were likely made to obtain those results. This helps mitigate issues with literature by helping the analyst narrow down which published values are most representative of the process under consideration.

7.4.2 General Carbon Fiber Production Process Considered in the Model

The model includes the three primary steps in fiber production defined in a previous section. The terms *stabilization* and *oxidation* are used interchangeably.

Three secondary steps are also included in the model. These steps include auxiliary processes that help with conversion of precursor materials to carbon fibers. These include cooling, stretching, spooling/winding, coating, sizing, surface treating, and washing of the fibers. Multiple instances of these sub-processes can occur during each secondary step, but they are grouped together for simplicity. Should a higher fidelity model be required, these secondary steps can be defined as a set of discrete sub-processes with a similar structure to the overall model.

7.4.3 Mass and Energy Flows

Primarily, fiber enters and leaves each step as a mass flow stream, but other mass flow streams can also enter and leave each step. For the primary steps, through gasses can enter and leave, carrying away evolved gasses. Entering each secondary step are sizing materials, coating materials, surface treatments, washing solutions, and so on. Out of each secondary step flows excess of these materials and additional waste products that are removed from the fiber. Obviously, the overall mass of the system must be conserved. Since gasses are being evolved from the fiber and various coatings may be added to the fiber, the mass of the fiber does not remain constant through the process.

Energy enters and leaves each step contained in the mass flow streams. The primary steps occur at elevated temperatures, requiring heat input. Energy can also leave both the primary and secondary steps as heat due to losses and non-ideal conditions. These heat transfer terms do not include energy carried out by the mass flow streams.
Work energy is assumed to flow into each of the secondary steps. These terms represent energy required to run various mechanical processes, though such processes typically occur both during the primary and secondary steps. For simplicity, this work energy is attributed in this model to the secondary steps.

An energy generation term is considered during the stabilization step. This is included since oxidation of precursor materials during stabilization is known to be exothermic.

7.4.3.1 Graphical Representation of the Production Model

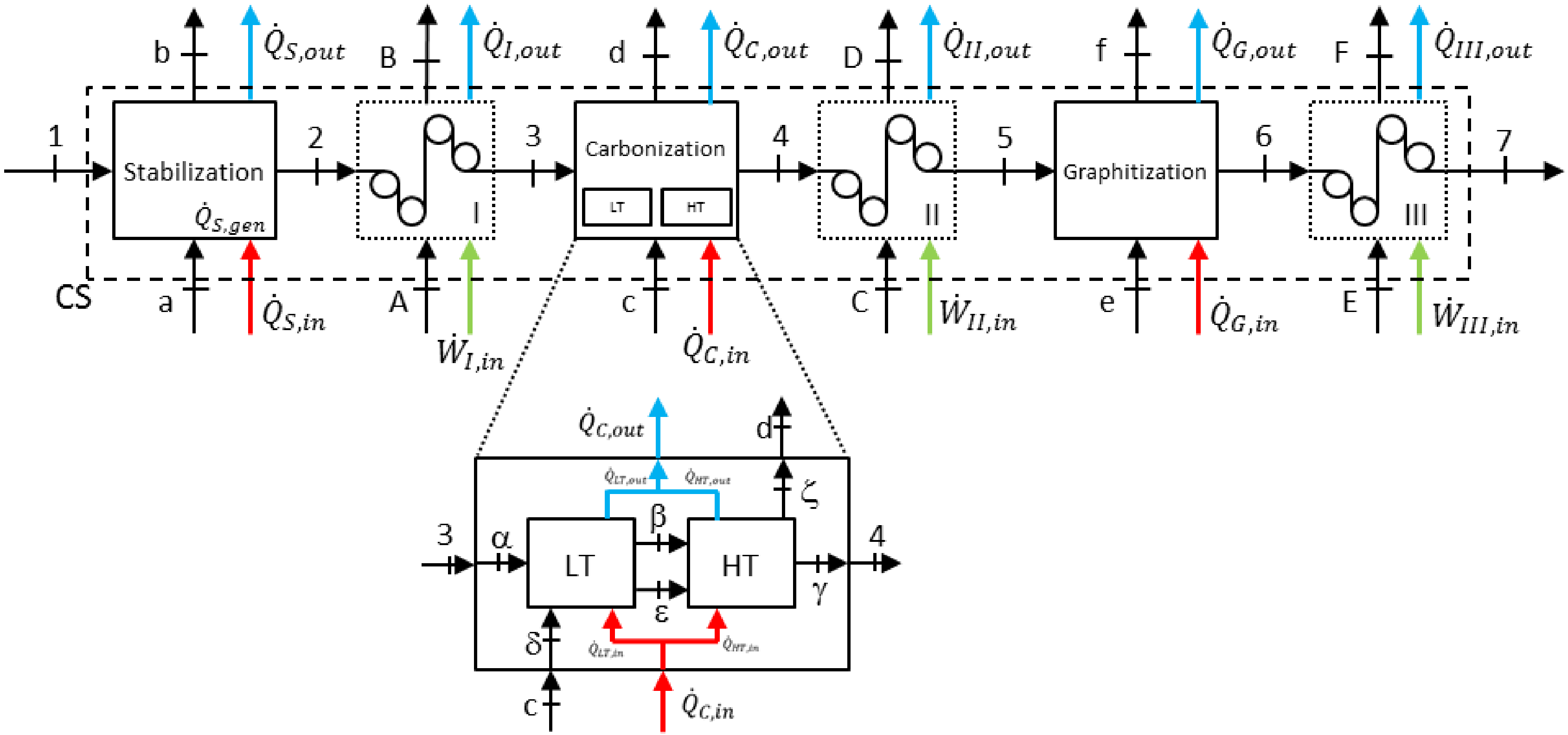
The carbon fiber production model can be represented visually to aid in analysis. Shown in Figure 33 are the six steps during the process and the mass and power considered. Listed are the expected contents of each mass flow stream.

The control surface (CS) defines the system boundary. The system as a whole can be represented as the sum of its parts. Each step can be individually analyzed, with the results summed to represent the system.

Power streams identified with $\dot{Q}_{in}$ correspond to the rate of heat energy added to each process to elevate the temperature of the step. Flows identified with $\dot{Q}_{out}$ correspond to the rate of heat energy output, likely due to losses. The rate of work energy flowing into each of the secondary processes identified as $\dot{W}_{in}$. Subscripts identify with which step the power flow is associated. Since stabilization is known to be exothermic, $\dot{Q}_{S,gen}$ is included to represent the rate of heat generation.

Carbonization often occurs in practice in two steps. The first step is a low temperature (PRe Consultants) heat treatment of the fibers, and the second is a high temperature (HT) heat treatment. To reflect this, the carbonization step is broken down into two sub-processes and structured similarly to the main production model.

The fundamental power balance equation given in Equation 21 can be applied to the carbonization sub-process. As with the overall process, the sub-process can be normalized such that results are specific to a unit mass of carbon fiber being produced.



1: Precursor
2: Stabilized Precursor
3: Treated Stabilized Precursor
4: Carbonized Fiber (Type II)
5: Treated Carbon Fiber
6: Graphitized Fiber (Type I)
7: Final Carbon Fiber

a: Oxidizing Through Gas
b: Excess Oxidizing Gas & Off-Gasses
c: Through Gasses
d: Excess Through Gasses & Off-Gasses
e: Through Gasses
f: Excess Through Gasses & Off-Gasses

A: Treating, Washing, Coating Material
B: Unconsumed Waste
C: Treating, Washing, Coating Material
D: Unconsumed Waste
E: Treating, Washing, Coating Material
F: Unconsumed Waste

α: Stabilized Precursor (identical to (3))
β: Fiber After LT Carbonization
γ: Fiber After HT Carbonization (identical to (4))
δ: Through Gasses (identical to (c))
ε: Excess Through Gasses & Off-Gasses
ζ: Excess Through Gasses & Off-Gasses

Figure 33: Graphical representation of the carbon fiber production process under consideration with the carbonization sub-processes defined

7.4.4 Mathematical Calculation

The thermodynamic power balance equation for an open system is used. The system of interest is the six step process outlined above, and all of the corresponding mass and energy flow rates into and out of the process. The rate of change of energy of the process is a function of the net rate of heat energy flow out of the system, the net rate of work energy flow into the system, the sum of energies associated with mass flow rates into and out of the system, and finally the rate of energy generation within the system. The general form of the equation is shown in Equation 21. This equation can be applied individually to each step of the overall process, or to the process as a whole.

$$\frac{dE}{dt} = \dot{Q}_{in} - \dot{W}_{out} + \sum_{in} \dot{m}_{in}(h + e_K + e_P)_{in} - \sum_{out} \dot{m}_{out}(h + e_K + e_P)_{out} + \dot{Q}_{gen} \quad (21)$$

An initial assumption can be made that the system is a steady state process, so the rate of change of energy of the system (*dE/dt*) is zero. Next, it is assumed each mass flow stream is an incompressible solid (fiber flow streams) or an ideal gas (through and evolved gasses). Thus, the specific enthalpy of a mass flow stream to be calculated, using Equation 22.

$$h = cT \quad (22)$$

Finally, it can be assumed that kinetic and potential energies associated with the mass flow streams is small compared to other terms. Combining these three assumptions, the final energy balance equation simplifies to Equation 23.

$$0 = \sum_{in} \dot{Q}_{in} - \sum_{out} \dot{Q}_{out} + \sum_{in} \dot{W}_{in} + \sum_{in} \dot{m}_{in} h_{in} - \sum_{out} \dot{m}_{out} h_{out} + \dot{Q}_{gen} \qquad (23)$$

Equation 21 is a power balance equation, but an energy balance is required to determine mass specific life cycle inventory information. Therefore, all terms in Equation 21 are to be normalized by a final flow rate of carbon fiber out of the overall process, resulting in Equation 24.

$$0 = \sum_{in} q_{in} - \sum_{out} q_{out} + \sum_{in} w_{in} + \sum_{in} \frac{m_{in}}{m_{cf}} h_{in} - \sum_{out} \frac{m_{out}}{m_{cf}} h_{out} + q_{gen} \qquad (24)$$

The resulting terms are thus normalized for the production of a unit mass of carbon fiber.

7.5 Case Specific Life Cycle Inventory

7.5.1 The Unknown

This particular calculation determines the energy required to produce 1 kg of Type II carbon fibers, which is used in the LCI for the fibers. Literature provides relative quantities of material inputs and emissions. This calculation uses this information from literature to calculate energy requirement and normalizes the amount of each material input and emission for 1 kg of Type II carbon fibers. This result is used for the LCI of producing 1 kg of Type II carbon fiber to be entered into SimaPro.

7.5.2 Calculation Procedure for Carbon Fiber Production Model

The general modeling procedure was described earlier in this chapter. The specific steps in this process are shown graphically in Figure 34.

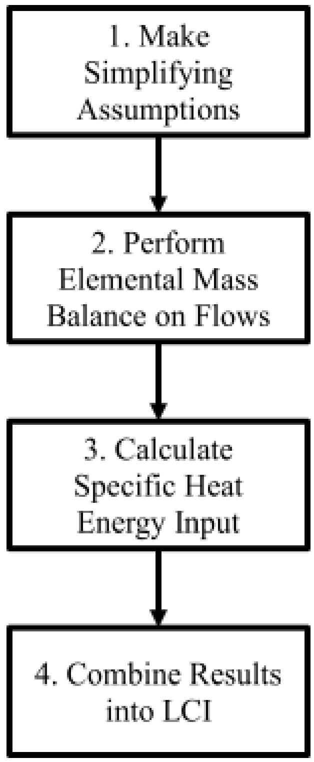


Figure 34: Graphical representation of calculation procedure in the Carbon Fiber Production Model

The detailed procedure is as follows:

1. Make simplifying assumptions based on the amount of data available. This simplifies the flow chart presented in Figure 33 and makes it possible to solve Equation 24.

2. Perform and elemental mass balance on each step of the process to determine mass flow rates for each of the remaining flow streams. This is performed using known values from literature.

3. Using the mass flow rates calculated in Step 2 and some additional data from literature, apply Equation 24 to solve for the specific heat energy input into each step.

4. Combining results from both the mass balance and energy calculation gives the final LCI used for the production of carbon fibers.

The normalized results from this procedure are the inputs to the SimaPro LCI entry for carbon fibers. These results are summarized in and tabulated the exact SimaPro inputs are found in Table C 4 in Appendix C.

7.5.3 System Boundary and Simplifying Assumptions

The system boundary is as represented in Figure 33, with the upstream boundary after the production of precursor material, but before precursor oxidation and the downstream boundary after graphitization step, but before the fibers are committed or consumed in product manufacturing.

It is necessary to make several simplifications to the complex model due to limited resources and the availability of data. The following simplifications are made:

- Only stabilization and carbonization are included, reflecting intermediate modulus fiber production.
- Only cooling is included in secondary steps (though the final result is adjusted for later based on literature data to reflect secondary steps)
- The exotherm during oxidation is neglected.
- The primary processes are performed in ideal ovens, under ideal conditions.
- The carbonization process is divided into the LT and HT sub-processes as described earlier.

- All results are normalized for the production of one unit mass of carbon fiber at location (7).

The maximum temperature of each process is approximated from literature. (Fitzer 1989; Fitzer and Frohs 1990)

- Stabilization: 260° C
- Carbonization (LT): 1000° C
- Carbonization (HT): 1800° C

Mass streams entering each of the primary steps are assumed to be at room temperature (27°C). Streams exiting a step are assumed to be at the maximum temperature of the process. The secondary processes must, by necessity, cool the fiber streams to room temperature.

7.5.4 Mass Flows

It is assumed that the precursor material is homopolymer polyacrylonitrile (PAN) that is already spun and ready to be stabilized in an oxidation step. It is known from literature (Stry 2012) that 52,000 kg/hr of air is consumed for a 432 kg/hr (input of PAN) oxidation oven. From this, it can be assumed that approximately 120 kg of air is required at (a) to properly oxidize 1 kg of PAN flowing in at (1).

The contents of stream (b) are a combination of unconsumed air from (a) and gasses evolved during the oxidation process. The evolved off-gasses can be approximated from literature, with values given in Table 33. Values are given as the mass of off-gas evolved per unit mass of PAN entering the process.

Table 33: Off-gasses evolved during stabilization, masses of off-gases normalized for 1 kg of fiber entering into the step

Off-Gas Molecule	(Morgan 2005) kg_{out}/kg_{in}	(Fitzer, Frohs et al. 1986) kg_{out}/kg_{in}
HCN	0.022	0.039
H2O	0.196	0.037
CO2	0.075	0.129
CO	0.01	0
NH3	0.002	0

The elemental breakdown of PAN entering at (1) is known from literature (Fitzer 1989). It is assumed that the PAN is stabilized such that the oxygen content is 16.5%, which is within a reasonable range also according to literature (Fitzer and Frohs 1990). This, along with the information in Table 33 is used to perform a mass balance to determine the elemental breakdown and the total mass of the stabilized PAN fibers as well as the makeup of the exhaust at (b) and stream (2). It is assumed that the secondary processes only cool the fiber, otherwise making the flow at stream (3) identical to stream (2). The results of the elemental mass balance on streams (b) and (2) are shown in Table 34. These results are used to perform a mass balance on the fiber, the results of which are shown in Table 37.

Table 34: Elemental mass balance on off-gasses evolved during stabilization, normalized for 1 kg of PAN flowing into the step

Off-Gas Molecule	Molecular Weight (kg/mol)	Average (from Table 33)		Carbon	Nitrogen	Hydrogen	Oxygen
		kg_out/ kg_in	mol_out/ kg_in	kg/kg_in	kg/kg_in	kg/kg_in	kg/kg_in
HCN	0.027	0.030	1.118	0.013	0.016	0.001	0.000
H2O	0.018	0.117	6.468	0.000	0.000	0.013	0.103
CO2	0.044	0.102	2.320	0.028	0.000	0.000	0.074
CO	0.028	0.005	0.179	0.002	0.000	0.000	0.003
NH3	0.017	0.001	0.056	0.000	0.001	0.000	0.000
Total		*0.255*		*0.043*	*0.016*	*0.014*	*0.181*

A similar elemental mass balance is performed on the carbonization step. It is gathered from literature (Harper International 2009) that about 12.5 kg of nitrogen gas are consumed at stream (c) for every kilogram of stabilized PAN flowing in at stream (3). Looking at the carbonization sub-processes, the off gasses produced during carbonization can be gathered from literature, according to Table 35.

Table 35: Off-gasses evolved during carbonization, masses of off-gases normalized for 1 kg of fiber entering into the step

Off-Gas Molecule	(Bromley 1971)				(Fitzer and Frohs 1990)		
	kg_{out}/kg_{in}	kg_{out}/kg_{in}	kg_{out}/kg_{in}	kg_{out}/kg_{in}	kg_{out}/kg_{in}	kg_{out}/kg_{in}	kg_{out}/kg_{in}
H2	0.003	0.004	0.005	0.039	0.012	0.008	0.005
N2	0	0	0	0	0.056	0.017	0.031
CO	0.022	0.01	0.013	0.055	0.014	0.017	0.035
CH4	0	0.005	0.001	0.06	0.02	0.01	0.003
CO2	0.124	0.078	0.076	0.054	0.022	0.035	0.088
NH3	0.057	0.068	0.078	0.024	0	0.044	0
H2O	0.082	0.076	0.102	0.063	0.126	0.119	0.202
HCN	0.179	0.165	0.126	0.079	0.07	0.095	0.135

The average amounts of each gas evolved are assumed while performing an elemental mass balance on the carbonization step. The results from this elemental mass balance are shown in Table 36. These results are used to perform a mass balance on the fiber, the results of which are shown in Table 37.

Table 36: Elemental mass balance on off-gasses evolved during carbonization, normalized for 1 kg of stabilized PAN flowing into the step

Off-Gas Molecule	Molecular Weight (kg/mol)	Average (from Table 35)		Carbon	Nitrogen	Hydrogen	Oxygen
		kg_out/ kg_in	mol_out/ kg_in	kg/kg_in	kg/kg_in	kg/kg_in	kg/kg_in
H2	0.002	0.011	5.371	0.000	0.000	0.011	0.000
N2	0.028	0.015	0.529	0.000	0.015	0.000	0.000
CO	0.028	0.024	0.846	0.010	0.000	0.000	0.014
CH4	0.016	0.014	0.881	0.011	0.000	0.004	0.000
CO2	0.044	0.068	1.549	0.019	0.000	0.000	0.050
NH3	0.017	0.039	2.276	0.000	0.032	0.007	0.000
H2O	0.018	0.110	6.104	0.000	0.000	0.012	0.098
HCN	0.027	0.121	4.487	0.054	0.063	0.005	0.000
Total		*0.402*		*0.093*	*0.110*	*0.038*	*0.161*

It is important to note that the off-gasses according to (Fitzer and Frohs 1990) did not assume homopolymer PAN, and it is unknown whether (Bromley 1971) did the same. Nevertheless, these values serve as a reasonable approximation for the purposes of this analysis. It can be assumed that off-gasses are evolved only from the fiber itself and no reaction occurs with the inert through gas entering at (c). To determine how much nitrogen is removed from the fiber, it is assumed that the nitrogen content of the fiber at (4) is 7%, according to (Fitzer 1989).

Next, an elemental mass balance was performed on the fiber through the entire process, assuming 1 kg of PAN flowing in at step (1). This was done using the results from Table 34 and Table 36. Assumptions made based on the literature described earlier are marked with an (*). The results on the fiber mass balance are found in Table 37.

Table 37: Elemental mass balance on the fiber flowing through the process

Streams	Fiber Mass (kg)	Carbon		Nitrogen		Hydrogen		Oxygen	
		Mass (kg)	%	Mass (kg)	%	Mass (kg)	%	Mass (kg)	%
1	1.000	0.680	68%*	0.260	26%*	0.060	6%*	0.000	0.000%*
2 & 3	1.109	0.637	57.413%	0.244	21.968%	0.046	4.119%	0.183	16.500%*
4 & 5	0.582	0.533	91.602%	0.041	7.000%*	0.003	0.591%	0.005	0.807%

These results balance the mass on the elements for 1 kg of PAN flowing into the process. These results were then normalized for 1 kg of Type II carbon fiber exiting at stream (5). Next, the normalized masses for each of the elements were used to calculate the amounts of each off-gas that is evolved during each step. This is the same elemental mass balance performed earlier, except in reverse. The results, normalized for 1 kg of carbon fiber output, are shown in a flow diagram of mass inputs and outputs to the process. This diagram is shown in Figure 35.

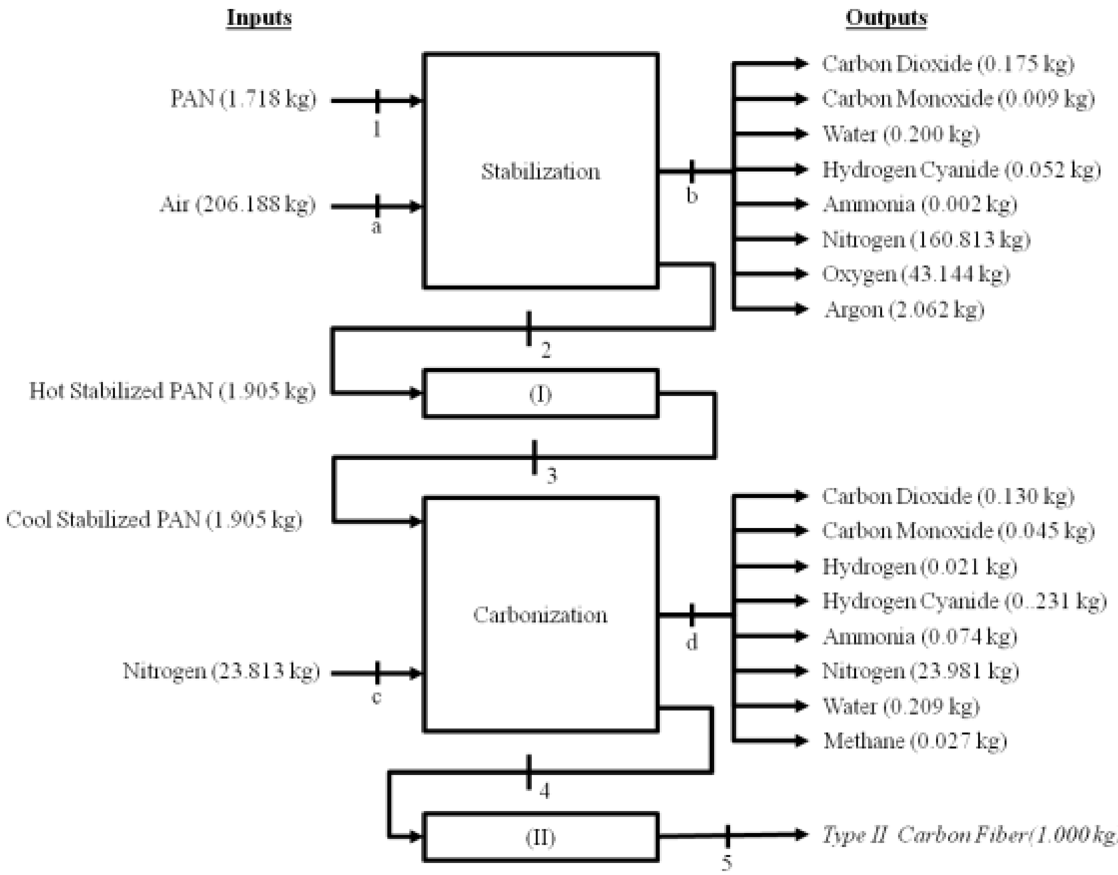


Figure 35: Mass flow diagram for the life cycle inventory of carbon fiber production based on the elemental mass balance and using Figure 33 as a reference

This is used to manually construct the LCI for the fiber in SimaPro. However, this diagram does not indicate the amount of energy consumed by the process, which is one of the issues that this model is striving to address. Energy is calculated in the following section.

7.5.5 Calculating Specific Energy Input into the Carbon Fiber Production Process

The assumptions listed earlier are applied to Equation 24, and it is rearranged to solve for the specific heat energy input, resulting in Equation 25 shown below.

$$q_{in} = \sum_{out} \frac{m_{out}}{m_{cf}} h_{out} - \sum_{in} \frac{m_{in}}{m_{cf}} h_{in} \quad (25)$$

Mass flows for each step shown in Figure 35 are plugged into Equation 25 to calculate the specific heat energy input into each step of the carbon fiber production process. Equation 25 is rearranged for the stabilization step and carbonization step to solve for the unknown specific heat energy input. These are shown in Equations 26 and 27, respectively.

$$q_{stabilization,in} = \left(\frac{m_{PAN}}{m_{CF}} h_{PAN} + \frac{m_{air}}{m_{CF}} h_{air}\right)_{T=T_{in}} - \left(\frac{m_{CO2}}{m_{CF}} h_{CO2} + \frac{m_{CO}}{m_{CF}} h_{CO} + \frac{m_{H2O}}{m_{CF}} h_{H2O} + \frac{m_{HCN}}{m_{CF}} h_{HCN} + \frac{m_{NH3}}{m_{CF}} h_{NH3} + \frac{m_{N2}}{m_{CF}} h_{N2} + \frac{m_{O2}}{m_{CF}} h_{O2} + \frac{m_{Ar}}{m_{CF}} h_{Ar} + \frac{m_{Stabilized\ PAN}}{m_{CF}} h_{Stabilized\ PAN}\right)_{T=T_{out}} \quad (26)$$

$$q_{carbonization,in} = \left(\frac{m_{Stabilized\ PAN}}{m_{CF}} h_{Stabilized\ PAN} + \frac{m_{N2}}{m_{CF}} h_{N2}\right)_{T=T_{in}} - \left(\frac{m_{CO2}}{m_{CF}} h_{CO2} + \frac{m_{CO}}{m_{CF}} h_{CO} + \frac{m_{H2O}}{m_{CF}} h_{H2O} + \frac{m_{HCN}}{m_{CF}} h_{HCN} + \frac{m_{NH3}}{m_{CF}} h_{NH3} + \frac{m_{CH4}}{m_{CF}} h_{CH4} + \frac{m_{O2}}{m_{CF}} h_{O2} + \frac{m_{H2}}{m_{CF}} h_{H2} + \frac{m_{CF}}{m_{CF}} h_{CF}\right)_{T=T_{out}} \quad (27)$$

The specific enthalpies (*h*) can be calculated using Equation 21 using the specific heat and the temperature of the mass flowing through the particular element. Masses (normalized for 1 kg of carbon fiber output), temperatures, and specific heats required to solve Equation 26 and Equation 27 are found in Table 38. The mass of carbon fiber (m_{CF}) is assumed to be 1 kg, reflecting the normalization.

Table 38: Masses, temperatures, and specific heats used to solve Equation 26 and Equation 27 to obtain specific energy input

Stream	Contents	Mass (kg/kg_Type II CF)	Temperature (K)	Specific Heat @T (kJ/kg-K)
1	PAN	1.718	300	0.842
2	PAN (stab.)	1.905	533	1.840
3	PAN (stab.)	1.905	300	0.842
4	CF (Type II)	1.000	2073	0.921
5	CF (Type II)	1.000	300	0.921
a	Air	206.188		
	N2	*160.827*	*300*	*1.040*
	O2	*43.300*	*300*	*0.918*
	Ar	*2.062*	*300*	*0.523*
b	CO2	0.175	533	1.035
	H2O	0.200	533	2.216
	HCN	0.052	533	1.328
	CO	0.009	533	1.071
	NH3	0.002	533	0.481
	N2	160.813	533	1.062
	O2	43.144	533	0.983
	Ar	2.062	533	0.523
c	N2	23.813	300	1.04
d	H2	0.021	2073	17.134
	N2	23.981	2073	1.288
	CO	0.045	2073	1.298
	CH4	0.027	2073	4.934
	CO2	0.130	2073	1.375
	NH3	0.074	2073	0.481
	H2O	0.209	2073	2.619
	HCN	0.231	2073	1.328

Plugging these values into Equation 26 and Equation 27 yields that the specific heat energy input into the stabilization step is approximately 53.6 MJ per kilogram of carbon fiber produced, while the specific heat energy input into the carbonization step is approximately 61.4 MJ per kilogram of carbon fiber produced. Combined, a total of about 115 MJ of energy is produced to produce 1 kg of Type II carbon fibers, according to this calculations. Model results are discussed further in the following section.

7.5.6 Model Results

In the previous section it was calculated that about 115 MJ of energy are required to produce 1 kg of IM carbon fibers. The model does not include any energy input for tensioners, spooling, cleaning, sizing, treating of effluents, etc. According to (Harper International 2009; Harper International 2012), these secondary processes can add approximately 100 MJ/kg to the energy consumed by the process, of which approximately 70 MJ (or 70%) is due to treating effluents. Adding 100 MJ/kg for processes not included in the case study raises the embodied energy of the fibers to 215 MJ/kg.

In the elemental mass balance shown in Table 37, the carbon content of the fiber was calculated to be 91.6% after carbonization, which is very near the 92% carbon content expected of Type II fibers. After graphitization, the carbon content jumps to 98.5%, as expected for Type I fibers. (Fitzer 1989)

The energy input was found above to be 215 MJ/kg, which is within the expected range of 100-400 MJ/kg seen in literature, but towards the lower end of the range. According to the results presented in the previous section from solving Equation 26, it is seen that 53.6 MJ/kg were consumed during stabilization, which is within the expected range according to literature (Harper International 2012), but tends towards the lower end. Likewise, the total energy required for carbonization is calculated in the previous section by solving Equation 25 to be about 61.4 MJ/kg, which is very near published values (Harper International 2012). However, according to literature (Morgan 2005), the energy ratio between LT treatment and HT treatment should be approximately 1:2, while it was calculated by the model to be closer to 1:1.

Based on the comparison of calculated results to published data (Harper International 2009; Harper International 2012), it is found that the carbon fiber production model's outputs are reasonable and that the results are valid.

The model defined above is sensitive only to the temperatures of processes and specific mass flow rates. This is by design as the model performs calculations using mass and energy balance equations, thus not permitting other parameters (like spool size, fiber diameter, etc.) to influence the results. It was found in literature (Harper International 2009; Harper International 2012), that the overall energy was sensitive not only to specific mass flow rates, but also total mass flow rates. It was seen that the per-kilogram environmental burdens of larger production lines were lower than the per-kilogram burdens of smaller lines that had a lower carbon fiber production rate. Capturing second order factors (spool size, overall flow rate, and fiber diameter) is beyond the scope of the model discussed here, though they are acknowledged.

Two major processes found in real world carbon fiber manufacturing plants were not modeled here in detail. These are post processing of effluents and heat recovery from post processing. Post processing of effluents reduces the concentrations of hazardous gasses evolved to meet emissions standards. Though this is not explicitly modeled, it is captured and accounted for in the 100 MJ/kg added at the beginning of this section to the specific heat energy input calculated in the previous section. Processing of effluents can be energy intensive, so efforts are made in real world production lines to recover some of this energy via heat exchangers that preheat air going into the stabilization ovens. These secondary processes can be added to the model as required, but were not considered in the case study according to the worst-case scenario assumption because there was not enough evidence to suggest that this was common practice in industry.

The final LCI for the production of carbon fibers is shown in Figure 36.

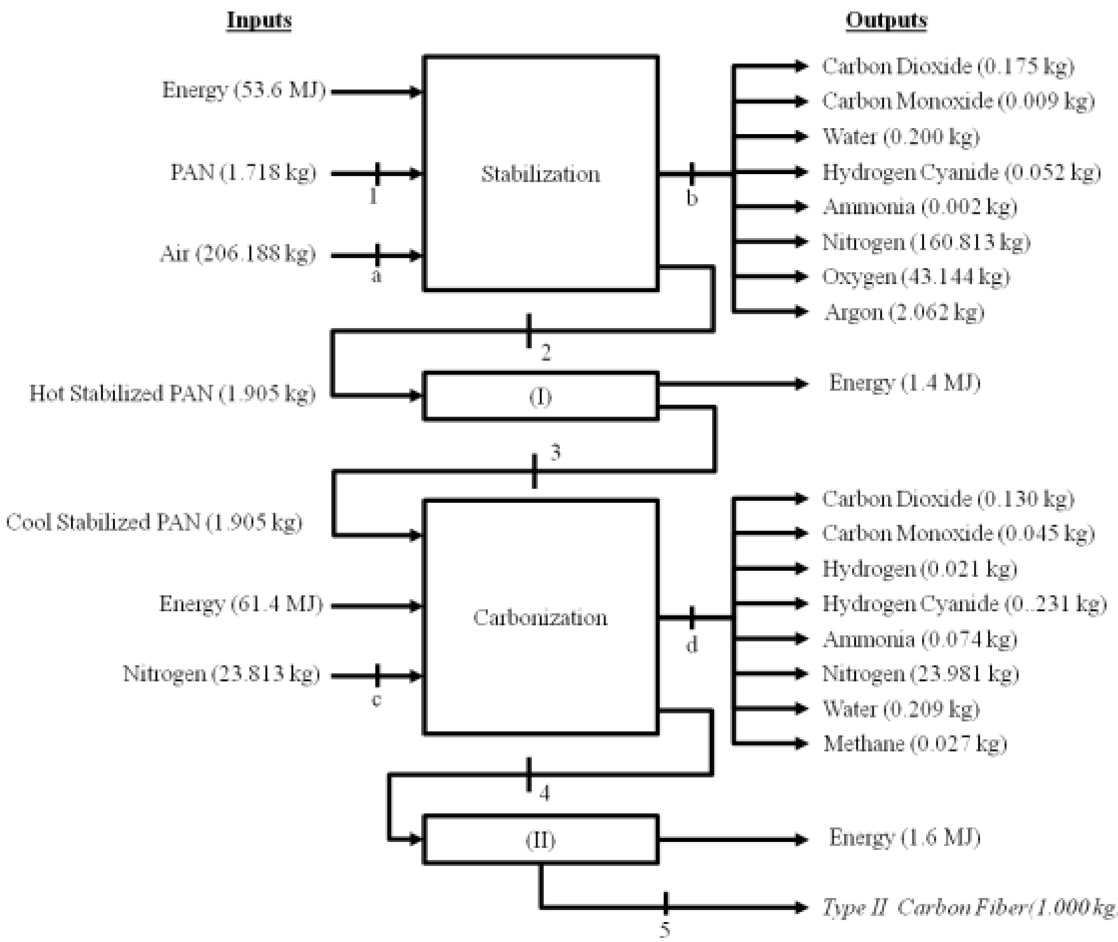


Figure 36: Final flows for the life cycle inventory for the production of carbon fibers

7.6 Matrix Materials

Carbon fibers must be held together by some material in a composite structure. The matrix can be made of virtually any material, but the structures used here are assumed to use a polymer matrix. Both thermoplastic and thermoset polymers may be used, but thermosets like epoxy are preferred due to their higher temperature tolerance, availability, and the relative ease with which they are worked. (Suzuki and Takahashi 2005)

It is assumed that epoxy is well understood material and it is not necessary to detail the production process here. Though (Suzuki and Takahashi 2005) cite a lower value for the embodied energy of epoxy production (76 MJ/kg), data found in (Granta 2012) that defines the embodied energy and carbon dioxide to be 126-140 MJ/kg and 6.83-7.55 kg/kg, which is similar to the database entry found in the EcoInvent database in SimaPro with has the name "Epoxy Resin, liquid, at plant/RER S." According to the worst-case scenario assumption, this entry in EcoInvent is considered a good representation of the matrix material used in carbon fiber reinforced polymer rocket structures.

7.7 The Composite Structure

A carbon fiber reinforced polymer composite structure is not necessarily equal parts reinforcement fibers and matrix material. For composites using an epoxy matrix, the mass fraction of carbon fiber is approximately 65-70% according to (Granta 2012), which is supported by (Suzuki and Takahashi 2005) who present a mass ratio of carbon fibers to epoxy matrix of 70:30. It is assumed here that the ratio of fibers to matrix is 70:30, by mass, in keeping with the worst-case scenario assumption as the embodied energy of the carbon fibers is considerably higher than that of the epoxy (215 MJ/kg as opposed to 76 MJ/kg).

The carbon fibers and matrix material are often combined shortly before they are shaped into a product. (Strong 2008) The environmental burdens of combining fibers with a matrix material are included during the manufacturing phase of the rocket and not in the upstream LCI for the CFRP. It is assumed a filament winding operation is used to produce CFRP components, and this process is detailed in (Suzuki and Takahashi 2005). The filament winding operation is described further in the following section.

7.8 Carbon Fiber Composite Component Manufacturing Processes

There are many ways to produce carbon fiber composite components. In the case of rockets, one particular method stands out. This is the filament winding process. In this process, carbon fiber tape is wound around a mandrel to produce a part. This tape is impregnated with a polymer matrix material, such as epoxy. To create more detailed shapes and features, trimming, cutting, and machining processes may be necessary. Filament winding is highly useful for large, axisymmetric components.

Carbon fiber composites are used in the payload fairings and inter-stage and inter-tank adapters of the Delta IV and Atlas V.(United Launch Alliance 2007; United Launch Alliance 2010) They are also used in the production of payload attachment fittings used for a variety of rockets, including the Ariane 5. (Ariane Space 2011) Carbon fiber composites are also commonly used in solid motor casings, such as those of the GEM-40 and GEM-60 boosters used on a variety of rockets. (Sutton and Biblarz 2001)

Propellant tanks can also be made from carbon fiber composites, and were used in the oxidizer tank on Space Ship 1. (Scaled Composites undated) NASA is also investigating their use in small to medium sized propellant tanks. (Center 2013) Nevertheless, it is not assumed that propellant tanks in the rockets being assessed here are made using carbon fiber composites because composite propellant tank manufacturing has not adopted widespread use in real world systems.

It is assumed that a filament winding process is used for all carbon fiber composite components used in the rockets in this analysis. There are no pre-existing LCI's for this process in SimaPro's databases, so one had to be created. Fortunately, (Suzuki and Takahashi 2005) provides good data on the required process steps and energy requirements for a filament winding process. This information is tabulated in Table 39 and is used to create the LCI for the filament winding manufacturing operation.

Table 39: Burdens of the filament winding process according to (Suzuki and Takahashi 2005)

Sub-Process	Energy Intensity (MJ/kg)
Resin Blending	0.1
Resin Coating	1.4
Resin Impregnation	2.1
Prepreg Winding	0.2
Atmosphere Control	20.8
Raw Material Storage	11.5
Prepreg Storage	3.4
Release Coated Paper Prodiction	0.5
Winding Fibers	2.7
Total	*42.7*

Typically, CFRP's used in aerospace undergo an additional autoclave process to cure the matrix material. This process helps improve the quality of the part by ensuring an even distribution of matrix material and by removing voids and pockets that could diminish the performance of the part. According to (Suzuki and Takahashi 2005), this can be an extensively energy intensive process, requiring as much as 600 MJ of energy per kilogram of part cured in an autoclave. With components massing hundreds to thousands of kilograms on a rocket, this can get very expensive in terms of energy and environmental impacts. Furthermore, there is the obstacle of physical size. Rocket components can be several meters in diameter, and many meters across. This can be prohibitively large for an autoclave process.

Out-of-autoclave processes seek to overcome the high energy costs of autoclave operations and issues caused by component size. These processes use other means, such as vacuum bags, to remove pockets and voids from composite structures. Out-of-autoclave processes do not restrict the size and shape of a component like autoclaves do, and can be used on large structures like airplane fuselages. (Gardiner 2011)

The final LCI for a CFRP component is made up of three parts: the carbon fiber, the epoxy matrix, and the filament winding manufacturing process. Each of these three parts was defined individually in the previous sections and they are combined to define the carbon fiber reinforced polymer material. The LCI for these indivudual elements of the carbon fiber reinforced polymer can be found both in previous sections and again in Appendix C.

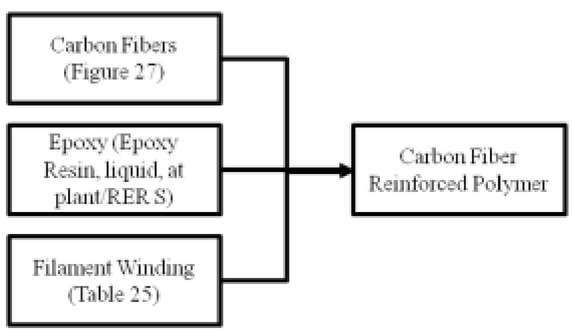


Figure 37: Components of a carbon fiber reinforced polymer inventory

7.9 Comparing the Carbon Fiber Reinforced Polymer to Other Materials

Carbon fiber reinforced polymers are used to replace aluminum and low alloy steels in this assessment. The relative impacts of producing 1 kg of each of these materials can be seen in Figure 38 with results tabulated in Table 40 and Table 41.

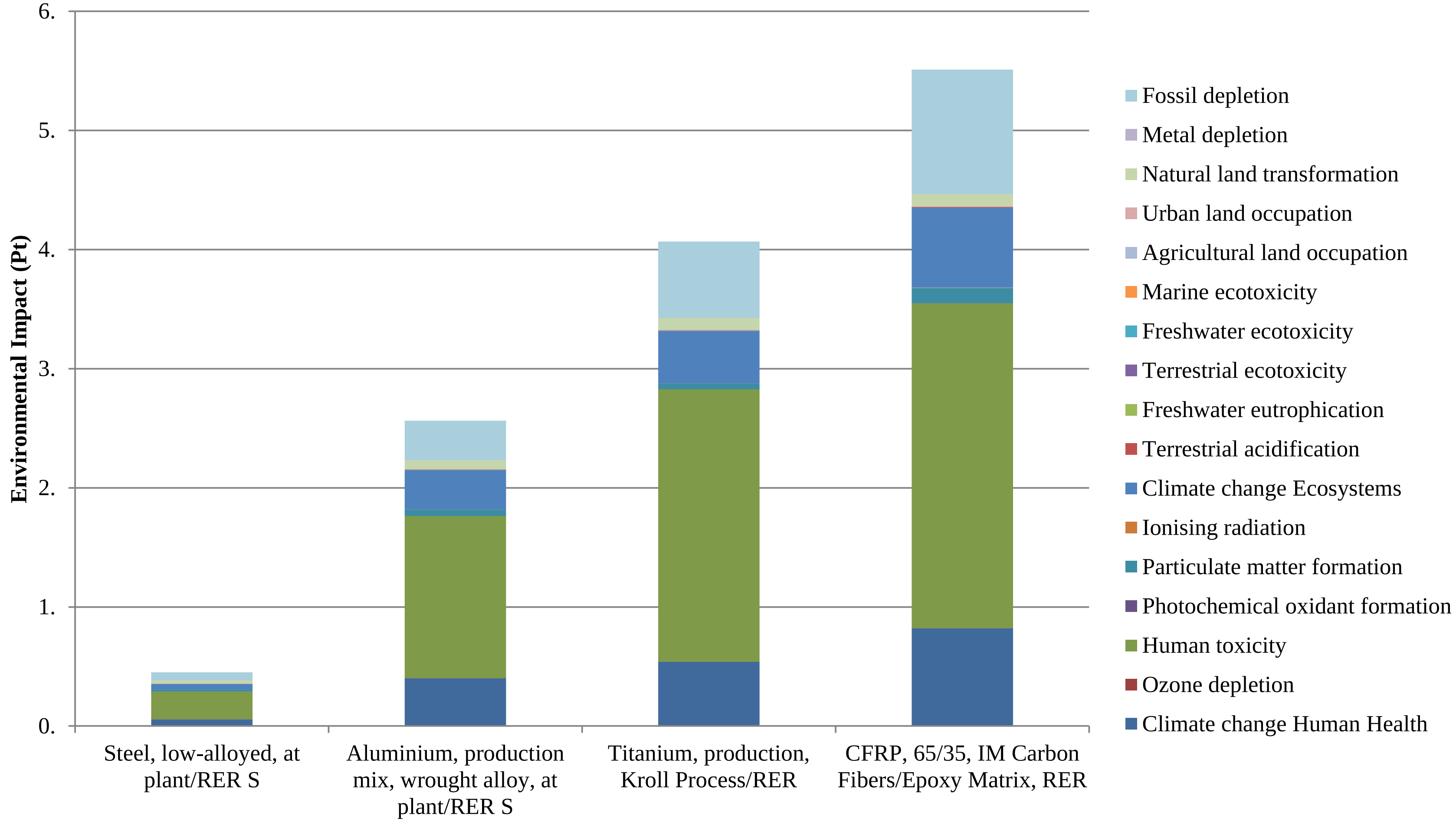


Figure 38: Comparing upstream environmental impacts of steel and aluminum to carbon fiber composites, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Table 40: Contribution of each impact category when comparing upstream environmental impacts (in Pts) of steel and aluminum to carbon fiber composites, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 1)

Material	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification
Steel, low-alloyed, at plant/RER S	5.58E-02	1.91E-06	2.35E-01	2.26E-06	1.57E-02	4.64E-05	4.56E-02	1.45E-04
Aluminium, production mix, wrought alloy, at plant/RER S	4.02E-01	1.70E-05	1.36E+00	1.05E-05	5.61E-02	4.56E-04	3.29E-01	1.02E-03
Titanium, production, Kroll Process/RER	5.39E-01	4.39E-05	2.29E+00	1.24E-05	4.88E-02	1.80E-03	4.40E-01	1.40E-03
CFRP, 65/35, IM Carbon Fibers/Epoxy Matrix, RER	8.21E-01	2.48E-05	2.73E+00	2.60E-05	1.28E-01	2.07E-03	6.71E-01	5.33E-03

Table 41: Contribution of each impact category when comparing upstream environmental impacts (in Pts) of steel and aluminum to carbon fiber composites, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 2)

Material	Freshwater eutrophication	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
Steel, low-alloyed, at plant/RER S	7.17E-05	7.17E-04	1.92E-05	7.52E-05	7.22E-04	5.09E-04	2.86E-02	1.64E-03	6.71E-02
Aluminium, production mix, wrought alloy, at plant/RER S	3.20E-04	3.32E-03	4.75E-05	2.31E-04	1.87E-03	1.50E-03	7.54E-02	2.64E-04	3.29E-01
Titanium, production, Kroll Process/RER	8.00E-04	1.20E-03	6.79E-05	3.00E-04	4.70E-03	1.50E-03	1.00E-01	7.49E-05	6.40E-01
CFRP, 65/35, IM Carbon Fibers/Epoxy Matrix, RER	9.55E-04	1.55E-03	8.10E-05	3.87E-04	4.16E-03	1.54E-03	1.02E-01	8.37E-05	1.04E+00

It can be seen that CFRP components have much higher embodied impacts than either steel or aluminum, which was expected. Each of the materials has relatively large impacts in the fossil depletion and climate change categories due to the consumption of fuel and release of carbon dioxide during energy production. The greatest impact is the found in the human toxicity category. For metal production, this includes chemicals used during harvesting and refining. In the case of carbon fibers, this is largely due to the harvesting and refining of the initial PAN fibers and the epoxy resin used for the matrix.

7.10 Chapter Summary

This chapter developed a life cycle inventory for the carbon fiber reinforced polymer used for light-weighting. This was done by developing a more detailed carbon fiber production model and calculating case specific inventory values that are more representative of the fibers used in a real world rocket. It was necessary to inspect carbon fibers more closely due to the pivotal role they play in this LCA.

The carbon fiber production model quantified the individual mass inputs and outputs to the process and calculated the energy consumption to be approximately 215 MJ/kg. This was found to be in the reasonable range based on literature discussed in the chapter. The results of this model were used to construct a life cycle inventory for the carbon fibers themselves.

This chapter also detailed and discussed the inventories for the epoxy matrix material and for the filament winding process used in producing a CFRP component. These are all combined to create the final inventory for the CFRP material used in light-weighted components.

8 LIFE CYCLE INVENTORY: COMBINED ROCKET LIFE CYCLE AND THE SIMAPRO MODEL

8.1 Overview of Chapter Contents

Previous chapters describe the rocket under consideration and assembly an inventory for all of the individual components of the rocket. This chapter details the phases of life that occur once these components are combined and the rocket functions as a single product during the use phase. The use phase has been defined as the launch of the rocket where propellants are burned, producing thrust and accelerating a payload to orbit. Detailed here is a life cycle inventory for the use phase of the rocket and the disposal of spent rocket components.

This chapter outlines how SimaPro represents the complete life cycle of the rocket and how this information fits into the life cycle assessment model.

8.2 Defining the Life Cycle in SimaPro

SimaPro has a special function where a product life cycle can be defined. When a new life cycle is defined, there are several fields that can be filled to represent the different stages of life. First, there is a field in which the product assembly can be specified. This is the exact rocket assembly that is being assessed and captures information about material harvesting and rocket manufacturing. In another field, use phase processes can be defined. These are the processes defined for burning of propellants. Finally, an end of life scenario can be added.

8.3 The Rocket Assembly

SimaPro allows for individual parts of a product to be defined and then assigned to an assembly that represents the product itself. A rocket is made up of multiple components, defined in Chapter 4 (beginning on page 64), which are each defined as an individual part in SimaPro. The mass, material makeup, and manufacturing process used to produce each component is defined when defining the part. The results from the PRSM can be hard coded into the model and then each part can be assigned to the appropriate assembly. This process can be time consuming and tedious and would require the creation of thousands of parts in SimaPro. An alternate approach is taken here to partially insert the calculations performed in the PRSM directly into SimaPro.

SimaPro has parametric functionality. This functionality is used to partially automate the creation of rocket assemblies, drastically reducing the time it takes to model and represent a new rocket. This is done in several steps, outlined in Figure 39.

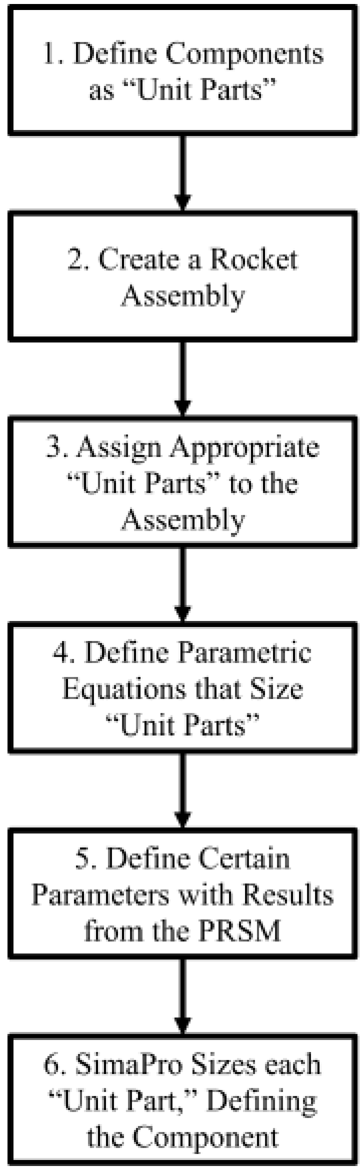


Figure 39: Process for defining rocket assembly in SimaPro

First, each component described in Chapter 4 is defined as a *unit part*. A part is created in SimaPro that represents the component. To each part, a material and a manufacturing process are assigned. The part is termed a *unit* part because the mass of the material consumed is defined to be 1 kg, and the manufacturing process is defined such that it represents the production of a 1 kg part. This is done for all of the components of a rocket.

Next, an assembly is created in SimaPro. The assembly element contains fields where the parts of the assembly can be defined. The unit parts representing the appropriate components are assigned to the assembly, depending on the configuration of the rocket that is to be modeled. Component assignments according to configuration are found in Chapter 4.

Rather than defining the mass of each component in the assembly, a parametric equation is entered that calculates the *quantity* of that component that is found in the assembly. Since each component was defined as a unit part with unit mass, this quantity represents the mass of the component. Since the parametric equation is effectively calculating the component's mass, the equation is identical to the MER used to size the component in the PRSM.

The MER's require certain inputs, which can be defined as parameters in the assembly entry for the specific rocket being sized. Specifically, the payload mass, propellant mass and inert mass of each stage is required, along with the specific propellant combination used on the rocket and its corresponding I_{sp} and O/F ratio. The parameters used are the final parameters calculated by the PRSM. Since the PRSM already iterated to size the rocket, entering parameters from the final result directly into SimaPro sizes the components accurately without the need for iterating. The specific values just described are entered as parameters in the assembly and SimaPro automatically calculates the quantity of each unit part contained by the assembly.

However, since 1 p (part) has a mass of 1 kg, this is equivalent to calculating the mass of a particular component on the rocket.

For example, a unit part is defined for the payload fairing. This part is made up of 1 kg of aluminum and contains an entry for manufacturing a 1 kg aluminum part. In the rocket assembly, it is defined that the rocket has a payload fairing and SimaPro requires that the quantity of payload fairings be defined. The quantity is defined parametrically using the MER for the payload fairing, which defines its mass to be 20% the mass of the payload. Next, the payload mass is defined (assume 1,000 kg for this example). SimaPro automatically calculates that the assembly contains a quantity of 1000 * 0.20 = 200 parts of the payload fairing. Since each part represents the material and manufacturing required to for 1 kg of that component, saying the rocket contains a quantity of 200 of the payload fairing is identical to defining the payload fairing to be 200 kg.

This process may seem complicated at first, but it allows for much faster and easier definition of rocket assemblies. Using the procedure defined above, each component is defined only once, rather than once for each rocket configuration. Defining each component as a unit part and then sizing it parametrically means that only half a dozen values must be entered manually for each rocket, rather than dozens. Once a single rocket assembly is set up, additional assemblies can be created and modeled quickly and relatively effortlessly. This process reduces the number of values that must be entered manually from thousands to hundreds, which makes it a task doable in a manner of days rather than weeks.

This also has the added benefit that uncertainty can be added more easily to the model. Since each unit part is defined as 1 kg, error can be added defining the part to be as small as 0.9 kg and as large as 1.1 kg. This has the same effect of adding ±10% uncertainty to the part. This is used in Chapter 10 during the uncertainty analysis.

An assembly is made for each rocket configuration under consideration. In this research, 140 different assemblies were created in SimaPro to represent the 70 pairs (baseline and light-weight) of rockets being assessed.

8.4 Material Harvesting Manufacturing

Each component defined in SimaPro has two sets of fields. The first allows for the material makeup of the component to be defined. The second allows the manufacturing processes used to produce the component to be defined. Material harvesting is captured in the SimaPro model when a material is assigned to a component in the rocket assembly. Likewise, the manufacturing processes used to produce each component are captured when they are assigned to the appropriate field in the component entry in the rocket assembly.

The specific data or database entry assigned and used to represent each material and manufacturing process is discussed in the appropriate chapter. Chapter 5 discusses the processes associated with propellants. The LCI's for non-propellant inert components of the rocket (the rocket structure) are discussed in detail in Chapter 6. The previous chapter (Chapter 7) discusses the LCI for the carbon fiber composite material used for light-weighting.

8.5 The Use Phase

When defining the life cycle for a product in SimaPro, there is a field that allows an analyst to specify use phase processes. For a rocket, the use phase is assumed to only consist of burning propellants. This is captured in SimaPro by assigning the appropriate entry for burning the specific propellant combination used to the appropriate field in the rocket's life cycle. These entries for burning propellants are defined in Chapter 5 (beginning on page 99). The inventories for burning propellants reflect the consumption of 1 kg of the specific propellant combination, meaning that the SimaPro model needs only to specify the total propellant load consumed during launch to completely capture use phase impacts.

8.6 End of Life Scenarios

It is possible to reuse components from rockets for future missions. The Space Shuttle Solid Rocket Boosters are recovered after every mission and reused and companies like SpaceX are developing reusable liquid stages (SpaceX 2013). However, this analysis has adopted a worst-case scenario methodology for assessment, so no reuse or recovery of rocket components is considered.

The end of life scenario for the rocket is assumed to be effectively landfilling of the inert portion of the rocket in accordance to the worst-case scenario where it is assumed no part of the rocket is recovered and it is assumed that the rocket falls to Earth and lands in some downrange impact zone. Though some components of the rocket, such as upper stages, may be injected into orbit with the payload, it is assumed they eventually fall back to Earth as their orbit decays. For simplicity, it is assumed any stages injected into orbit do not burn up on re-entry. This is perhaps an area where additional detail can be added in future work to improve model fidelity. The main propellants (and RCS propellants) are assumed consumed during use, the payload is injected into orbit and its burdens are allocated to its life cycle, leaving only the inert portions of the rocket to fall to Earth and be effectively landfilled or disposed of in the ocean.

The inert portions of the rocket consist of structural materials as well as unspent propellants from residuals and reserves. The structural materials assumed used in the rocket are mostly environmentally benign and it is the landfilling of propellants that is assumed to be causing the bulk of the end of life environmental impacts.

Two scenarios are modeled to show the two extremes of what may occur with spent stages. The first scenario assumes that the stages fall into an ocean, as would be the case from coastal launches like from Kennedy Space Center, Florida. The second scenario assumes the spent stages fall on land, as would be the case of launches from Baikonur Cosmodrome, Kazakhstan. Stages landing on both land and in the ocean are assumed to be some combination of these two scenarios.

As spent stages are falling to Earth, unconsumed propellants can evaporate or otherwise be released into the atmosphere during descent. Literature suggests that approximately 50% of the propellants are released into the atmosphere before the stage and the remainder of the propellants reach the surface. (Kuzin 1997) It is assumed here that 50% of the remaining propellants are emitted into the atmosphere before the spent stage lands.

8.7 Geography and Transportation

Stakeholders involved in rocket operations span the globe. Materials are harvested, rockets are manufactured and launched, and spent stages fall across a wide range of geographical zones. From an absolute sense, this makes a big difference in terms of environmental impact. However, to answer the research questions proposed here, *relative* differences are what matter amongst the rockets being assessed. When comparing two rockets (one baseline and one light-weighted) to determine whether light-weighting has an environmental benefit, the specific geographical locations where the rocket experiences stages of its life should not play a major role in answering the research questions, so long as the same geographical assumptions are made about both rockets.

In this LCA, it is assumed that the rockets life cycle occurs primarily in Europe. This is plausible since there is a major rocket provider and operator based in Europe: The European Space Agency. This is useful since the databases and impact assessment methods SimaPro uses heavily favor European data. Should there be no Europe-specific data available, global data shall be used. In some cases, no geographic information is specified for certain data, in which case the best approximation is made using other factors.

With respect to transportation of components and materials from one location to the other (i.e.: transporting parts amongst factories), it is assumed that all transportation is neglected unless already included in a pre-existing LCI. It is assumed that transportation contributes little to the overall life cycle impacts of a rocket. Chapter 11 (beginning on page 255) contains an analysis that discusses the validity of this assumption in more detail, and how certain levels of transportation can affect the outcome of the LCA. It was found that transportation contributes a small amount to the lifetime impacts of a rocket. These contributions, though non-negligible, are small enough that they can be ignored at in this research without affecting the outcomes of the analysis.

8.8 Performing a Life Cycle Impact Assessment in SimaPro

For each of the 140 rocket configurations being assessed in this research, a life cycle entry is made in SimaPro. Assigned to each life cycle entry is the assembly representing the particular configuration, the use phase processes for burning propellants and the quantity of propellant burned, and the end of life scenario considered by the rocket.

Once all 140 life cycles are defined, an assessment can be performed. Assessments are performed by selecting one or multiple life cycles defined and running a simulation. The assessment is performed according specific impact assessment method selected and defined. SimaPro compiles the results from the impact assessment as a series of tables and graphs.

8.9 Including Uncertainty and the Monte Carlo Simulation

Due to the way each component and process was modeled as a unit part represented as a 1 kg component, uncertainty can be added easily into the model. SimaPro allows uncertainty to be defined for any values or fields representing the quantity of a part. It was assumed here that the uncertainty was some percent error from the calculated results. For instance, a ±10% error is represented by defining the unit part as being 1 kg, then defining that the unit part can be as light as 0.9 kg and as heavy as 1.1 kg.

For example, when the assembly calculates that the rocket has a quantity of 200 payload fairings, it is identical to say that the payload fairing on the rocket is sized as 200 kg. By defining the unit part of the payload fairing to be between 0.9 kg and 1.1 kg, the actual fairing can be as light as 180 kg or as heavy as 220 kg. This is identical to saying that the part is 200 kg, but the impacts can be as high low as a 180 kg component or as high as a 220kg component. This is also identical to saying that each individual environmental burden of the 200 kg part is assigned an error of ±10%. This uncertainty is used in Chapter 10 (beginning on page 239) during a Monte Carlo simulation that determines upper and lower bounds to the total uncertainty during the process.

9 Life Cycle Impact Assessment: Results and Discussion

9.1 Overview of Chapter Contents

This chapter presents the results of the primary Life Cycle Assessment on the 70 baseline rockets assessed. These 70 rockets represent each of the configurations under consideration before they are light-weighted. After a discussion of these results, this chapter describes how the environmental impacts of the 70 baseline rockets change as a result of light-weighting. Combined, there are 70 baseline, un-lightened rockets compared to 70 similar rockets that have been lightened, meaning a total of 140 different rockets are compared.

9.2 Functional Unit

Rockets with the same lift capacity to LEO can be compared directly to each other since each rocket is capable of satisfying the same mission objective. However, when comparing rockets of different lift capacities to LEO, a more general functional unit must be established.

The best way to compare rockets would be to use the impulse delivered by the rocket to the payload. In this way, both the payload mass and the delivered ΔV are taken into account. Two rockets with the same total impulse are assumed to be capable of fulfilling the same mission. Using a functional unit of a unit impulse, or normalizing impacts by the total impulse delivered by the rocket can help compare rockets of different sizes and different intended mission parameters. The ideal functional unit expressing impulse would be 1 kg-m/s delivered to the payload. This value represents what is needed to accelerate a 1 kg payload mass by 1 m/s. However, it is difficult to assign an intuitive meaning to this functional unit. Therefore, a slight modification to this unit is made.

It is assumed the rockets assessed here launch payloads to LEO, where the ΔV required to achieve orbit is assumed fixed at 9,000 m/s. With the ΔV fixed, the payload mass can be varied to reflect rockets of different sizes. Impacts can be normalized by payload mass to LEO. This is essentially the same as normalizing by total impulse since it has a mass component and a ΔV component, but it is more intuitive to think of lift capacity to LEO, than raw impulse.

The functional unit for this assessment is **1 kg of payload to LEO**.

This unit represents a fraction if the impacts a single rocket would experience. It can also be useful to normalize the results of the impact assessment for a single year of operation. According to (Federal Aviation Administration 2012), approximately 700,000 kg of payload was lifted to LEO during 2012. Multiplying the results normalized by the functional unit by 700,000 represents the total yearly global impacts of rocket launches to LEO.

9.3 Summary of Major Assumptions

9.3.1 Rocket Life Cycle, Configurations, and Sizing

The rocket life cycle includes the following processes. They are summarized in Figure 40, repeated here for clarity.

- Structural Material Harvesting (Material Harvesting)
- Propellant Production (Material Harvesting/Manufacturing)
- Structure Manufacturing and Assembly (Manufacturing)
- Launch/Propellant Consumption (Use)
- Spent Stage Separation (Transition from Use to Disposal)
- Spent Stage Impact in Land/Ocean (Disposal)

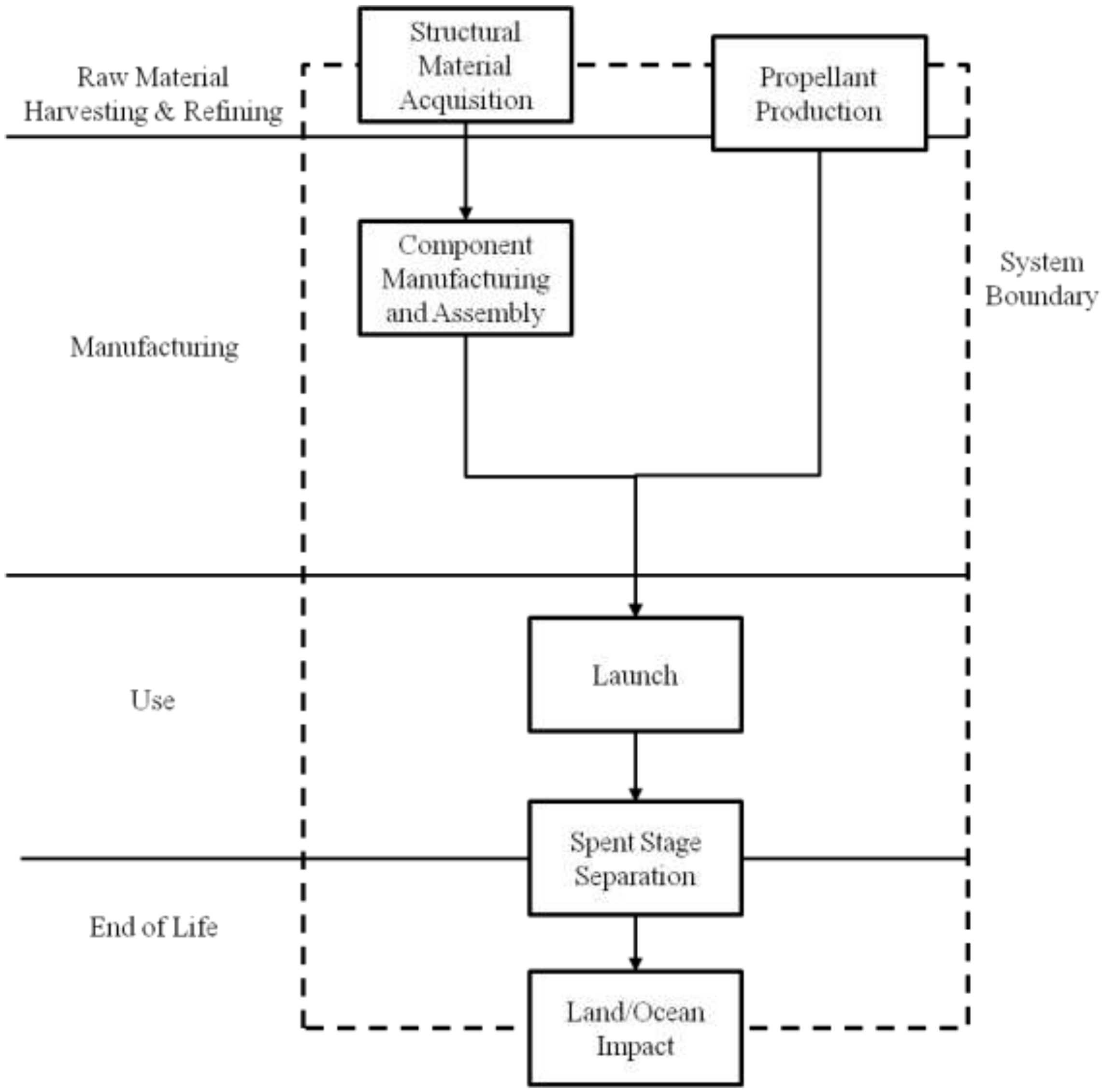


Figure 40: Rocket Life Cycle Description

There are seventy different rocket configurations assessed. These include four propellant combinations, eighteen lift capacities, and three staging options. The different configurations are outlined in Table 42, repeated here for clarity. Each of these seventy rocket configuration has a baseline (un-lightened) variant and a light-weighted variant, making a total of 140 rocket configurations that are assessed.

Table 42: Table describing the 70 different rocket configurations considered in this assessment

Payload Mass (kg)	Total Impulse (MM kg-m/s)	Two Stages	Three Stages	Four Stages
500	4.50	*(not sized)*	*(not sized)*	Solid
750	6.75	*(not sized)*	*(not sized)*	Solid
1,000	9.00	*(not sized)*	*(not sized)*	Solid
1,250	11.25	*(not sized)*	*(not sized)*	Solid
1,500	13.50	*(not sized)*	*(not sized)*	Solid
1,750	15.75	*(not sized)*	*(not sized)*	Solid
2,000	18.00	*(not sized)*	*(not sized)*	Solid
2,250	20.25	*(not sized)*	*(not sized)*	Solid
2,500	22.50	LOX/LH2	LOX/LH2	Solid
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
5,000	45.00	LOX/LH2	LOX/LH2	Solid
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
10,000	90.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
20,000	180.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
35,000	315.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
50,000	450.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
75,000	675.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
100,000	900.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
150,000	1,350.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	
200,000	1,800.00	LOX/LH2	LOX/LH2	*(not sized)*
		LOX/RP1	LOX/RP1	
		N2O4/UDMH	N2O4/UDMH	

The rocket is assumed to be made up of a limited number of generalized components. These components and their assumed material makeup are defined in Table

43. The way in which these components are assigned to different rocket configurations is described in detail in Chapter 4.

Table 43: Generalized rocket components, their function, and material makeup

Component	Function	Material
Structure		
Fuel Tank	store fuel	aluminum
Oxidizer Tank	store oxidizer	aluminum
Fore Inter-Stage Adapter*	connect current stage to next stage	aluminum
Aft Skirt*	protect aft section of the rocket	aluminum
Inter-Tank Adapter*	connect two propellant tanks	aluminum
Payload Fairing*	protect payload in the atmosphere	aluminum
Thrust Structure	connect engines to rocket	iron-based superalloy
Motor Case*	primary solid motor housing	low alloy steel
Protection		
Fuel Tank Insulation	insulate fuel tank	polyurethane foam
Oxidizer Tank Insulation	insulate oxidizer tank	polyurethane foam
Base heat Shield	protect base of rocket from engine heat	ceramic/glass foam
Motor Case Insulation	insulate motor casing from burning propellant	nitrile rubber
Propulsion		
Main Engines	primary propulsion	iron-based superalloy, aluminum, stainless steel
Main Propellant Feed Lines	feed propellants to engine	stainless steel
Gimbal	pivot engine to vector thrust	iron-based super alloy
Motor Nozzle	solid motor exhaust nozzle	graphite
Control		
RCS Engines	minor rocket turns, orientation, and positioning	cobalt, molybdenum, aluminum
RCS Oxidizer Tank	store RCS oxidizer	titanium
RCS Fuel Tank	store RCS fuel	titanium
RCS Propellant Feed Lines	feed RCS propellants to RCS engines	stainless steel
Avionics		
Guidance & Navigation	guide and navigate rocket	electronics
Communication & Tracking	communicate with ground control and track rocket	electronics
Data Processing	process rocket data	electronics
Environmental Control		
Thermal Control System	environmental control for payload	electronics
Other Non Cargo		
Motor Ingiter	ignite solid propellants	generic explosive
Ordinance	destroy rocket in case of emergency	generic explosive
Unused Propellants		
Main Propellant Residuals	excess main propellant in tanks and feed lines	(same as main propellants)
Main Propellant Reserves	excess main propellant	(same as main propellants)
Main Propellant Pressurant	maintain main propellant tank pressure	helium
RCS Propellant Residuals	excess RCS propellant in tanks and feed lines	(same as RCS propellants)
RCS Propellant Reserves	excess RCS propellant	(same as RCS propellants)
RCS Propellant Pressurant	maintain RCS propellant tank pressure	helium

Light-weighting is performed by reducing the mass of certain components, listed below, by 25%. The original material of these components (listed above) is substituted with CFRP's.

- Fore Inter-Stage Adapter
- Aft Skirt
- Inter-Tank Adapter
- Payload Fairing
- Motor Case

Rockets were initially sized assuming no CFRP's were used for light-weighting. The process is described in detail in Chapter 4, while some major assumptions are listed here for clarity. Once the seventy configurations were sized assuming no light-weighting, each was resized assuming the light-weighting assumption described above.

- Same propellant combination used for each stage
- O/F assumed constant for each stage (based on propellant)
- I_{sp} the same for each stage (based on propellant)
- Initial T/W when a stage fires is 1.35
- Inert mass fraction used to size RCS fixed at 0.1
- RCS assumed to provide a ΔV of 50 m/s to final stage

Assumed properties for the propellants and their combinations are summarized in Table 43.

Table 44: Assumed properties of different propellants in particular combinations

Propellants	$\rho_{oxidizer}$ (kg/m^3)	ρ_{fuel} (kg/m^3)	O/F Ratio	$I_{sp,sl}$ (s)	$I_{sp,vac}$ (s)	$I_{sp,used}$ (s)
LOX/LH2	1,141	70.85	5.5:1	318	450	425
LOX/RP1	1,141	800	2.25:1	293	333	315
N2O4/UDMH	1,443	790	1.5:1	283	312	300
Solid	1,760		*n/a*		284	285

9.3.2 Propellant and Structural Material Life Cycle Inventory

Propellant production is represented with material harvesting and manufacturing of the propellant in the same process. Close approximations for inventories for certain propellants are found in the EcoInvent database, while other inventories are constructed using literature data. It is assumed the use phase of the rocket includes only the consumption (burning) of these rocket propellants.

Close approximations for most structural materials are found in the EcoInvent database, though some inventories had to be created from literature data. Structure manufacturing processes are generalized using inventory entries from EcoInvent that represent industry average manufacturing for certain materials.

The database entries from EcoInvent are the best data available at this time and are assumed to be adequate representations of the system for the purposes of this LCA.

9.3.3 Carbon Fiber Reinforced Polymer Life Cycle Inventory

It is assumed an intermediate modulus (IM) carbon fiber is used. The matrix material is assumed to be epoxy, and the composite structure contains a 70:30 mix (by mass) of fibers to matrix material.

The following properties of carbon fiber production are assumed. These assumptions are representative of the IM fibers being used.

- Only stabilization and carbonization are included, reflecting intermediate modulus fiber production.
- Only cooling is included in secondary steps (though the final result is adjusted based on literature data to reflect secondary steps)
- The exotherm during oxidation is neglected.
- The primary processes are performed in ideal ovens, under ideal conditions.
- The carbonization process is divided into the LT and HT sub-processes
- All results are normalized for the production of a unit mass of carbon fiber

- Stabilization: 260° C
- Carbonization (LT): 1000° C
- Carbonization (HT): 1800° C

9.3.4 Additional Analyses

For the uncertainty analysis, three levels of error are assumed. These are based on error seen in comparing the PRSM results to real world rockets.

- Low (±10%)
- Moderate (±25%)
- High (±50%)

Different light-weighting amounts are also assumed in addition to the original 25% mass reduction assumption. These light-weighting amounts are 10% and 50%.

When assessing the influence of transportation the rocket's lifetime impacts, transportation by truck-freight, rail-freight, and air-freight are assumed.

To put the environmental impacts of rockets into a global perspective, it is assumed that 700,000 kg of payload is launched to LEO in a year.

9.4 Results from the Impact Assessment, Without Including Light-Weighting

9.4.1 General Results for a Complete Rocket Using the Single Score Indicator

Before results are normalized by the functional unit, some general behavior of each rocket configuration is investigated. This is done by looking at the single score indicator for a complete baseline rocket of each general configuration.

First, results are presented for the baseline rockets without considering light-weighting. This is done to help establish a baseline for comparison when light-weighting is included and to help identify any peculiarities or interesting behavior that may be useful in understanding the role light-weighting plays. These results are general, high level results using the single score indicator. Since rockets are not being directly compared to each other at this stage, results are not normalized by the functional unit. More specific results and analysis is found in subsequent sections.

Figure 41 shows the results from an environmental impact assessment of a two stage LOX/LH2 rocket capable of lifting 10,000 kg to LEO. The results are shown using the single score indicator to represent environmental impacts. Only the eleven most significant processes in the life cycle are shown in the flow diagram, while the contribution to the single score indicator of every process modeled can be found in Table 45. Results in Table 45 are normalized by the functional unit of 1 kg payload mass to LEO.

It is interesting to note that for this particular rocket, the majority of its life cycle impacts, 82.3%, are due to inert components. These impacts are dominated by only a handful of components, like the onboard electronics and engines. Propellants contribute only 17.2% to the life cycle environmental impacts of the rocket.

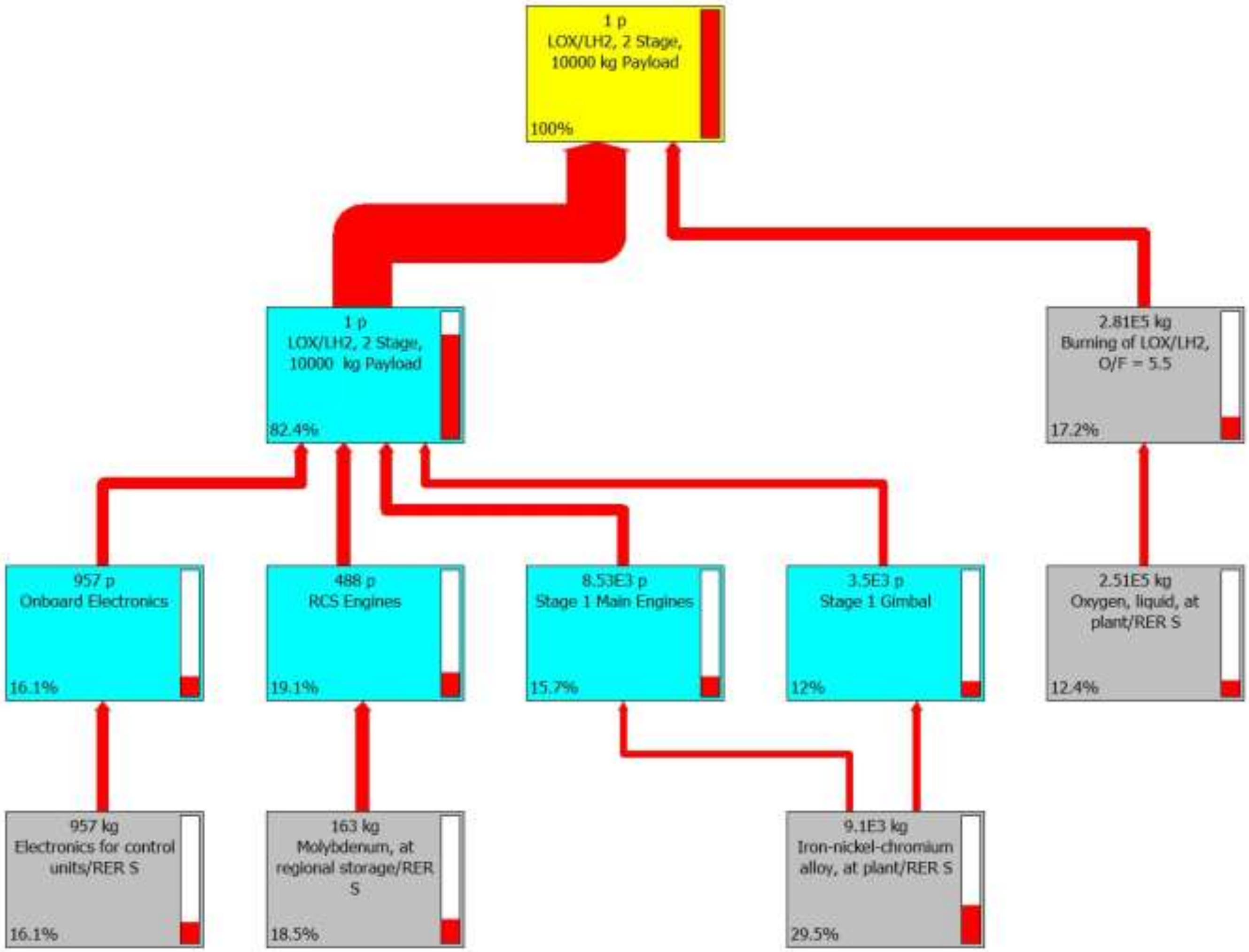


Figure 41: SimaPro LCA results using the ReCiPe 2008 Egalitarian Endpoint single score impact for a 2 stage LOX/LH2 rocket with 10,000 kg to LEO

Table 45: Contribution of each process to the lifetime environmental impacts of a 2 stage, LOX/LH2 rocket capable of 10,000 kg to LEO, with impacts normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint method

Process	**Impact (Pt)**
Total of all processes	*2.38E+01*
Iron-nickel-chromium alloy, at plant/RER S	7.00E+00
Molybdenum, at regional storage/RER S	4.40E+00
Electronics for control units/RER S	3.82E+00
Oxygen, liquid, at plant/RER S	2.96E+00
Aluminium, production mix, wrought alloy, at plant/RER S	1.73E+00
Hydrogen, liquid, at plant/RER S	1.33E+00
Helium, at plant/GLO S	6.99E-01
Aluminium product manufacturing, average metal working/RER S	5.66E-01
Steel product manufacturing, average metal working/RER S	4.34E-01
Steel, electric, chromium steel 18/8, at plant/RER S	3.37E-01
Chromium steel product manufacturing, average metal working/RER S	2.15E-01
Polyurethane, rigid foam, at plant/RER S	1.12E-01
Cobalt, at plant/GLO S	4.75E-02
Metal product manufacturing, average metal working/RER S	4.29E-02
Ammonia, liquid, at regional storehouse/RER S	1.73E-02
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	1.21E-02
Dimethylamine, at plant/RER S	1.16E-02
Chlorine, liquid, production mix, at plant/RER S	1.04E-02
Electricity, production mix RER/RER S	9.88E-03
Burning of N2O4/UDMH, O/F = 1.5	4.69E-03
Foam glass, at plant/RER S	1.05E-03
Nitrogen, liquid, at plant/RER S	5.02E-04
Petroleum coke, at refinery/RER S	1.84E-05
Magnesium, at plant/RER S	1.68E-05
Natural gas, high pressure, at consumer/RER S	1.06E-05
Argon, liquid, at plant/RER S	2.37E-06
Titanium, Kroll Process, RER	3.45E-07
Sodium chloride, powder, at plant/RER S	-3.73E-03

Figure 42 shows the results from the same assessment done on the 3 stage LOX/LH2 rocket capable of lifting 10,000 kg to LEO. Normalized results for the contribution of each process to the lifetime impacts are shown in Table 46. It is interesting to note how the 3 stage rocket's lifetime environmental impacts shift even more heavily towards the inert portions and away from the propellants. This is to be expected as rockets with more stages have a higher inert mass fraction, meaning the ratio of inert structure to propellant mass is higher. (Sutton and Biblarz 2001)

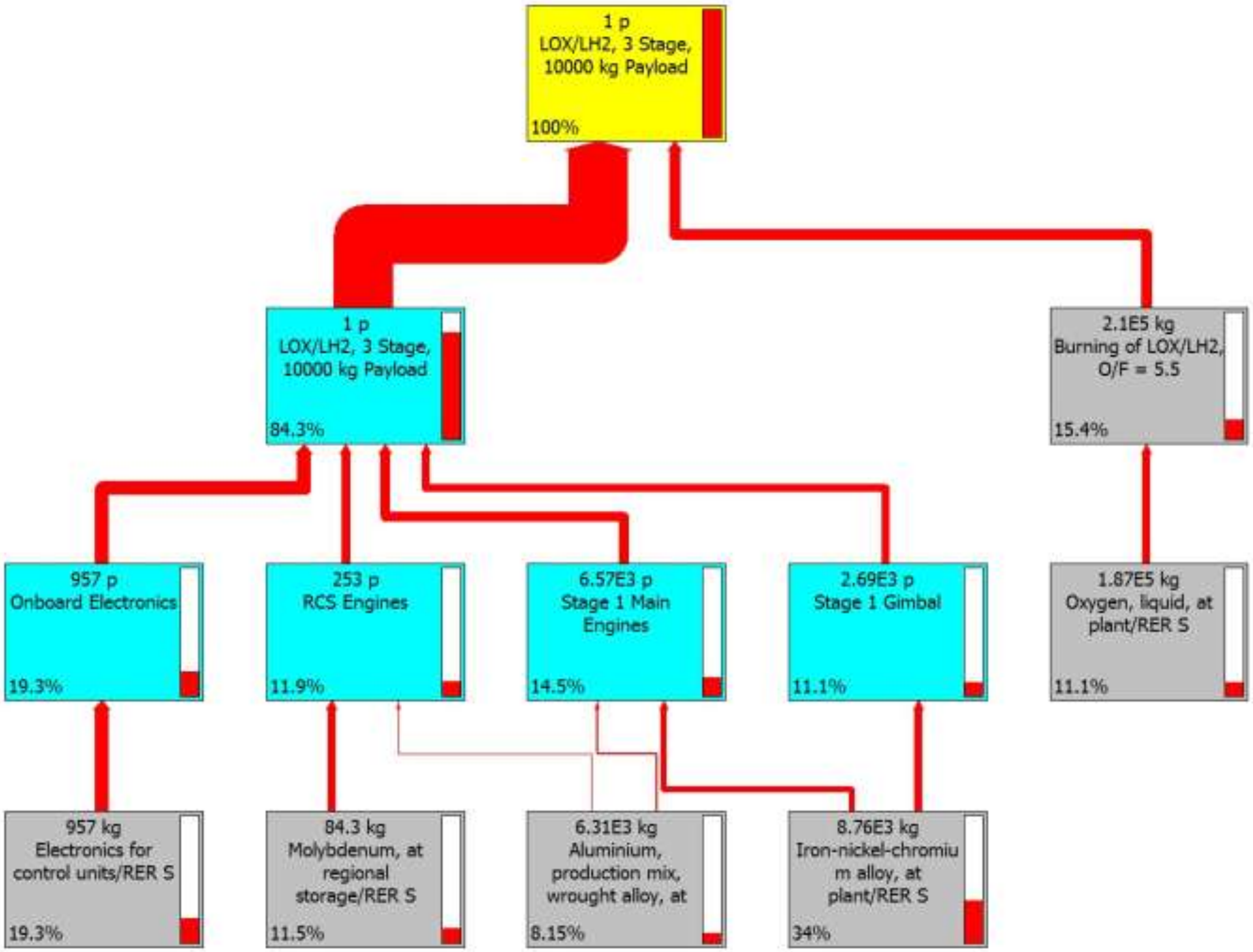


Figure 42: SimaPro LCA results using the ReCiPe 2008 Egalitarian Endpoint single score impact for a 3 stage LOX/LH2 rocket with 10,000 kg to LEO

Table 46: Contribution of each process to the lifetime environmental impacts of a 3 stage, LOX/LH2 rocket capable of 10,000 kg to LEO, with impacts normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint method

Process	Impact (Pt)
Total of all processes	*1.99E+01*
Sodium chloride, powder, at plant/RER S	-1.93E-03
Titanium, Kroll Process, RER	1.86E-07
Argon, liquid, at plant/RER S	1.28E-06
Natural gas, high pressure, at consumer/RER S	5.74E-06
Magnesium, at plant/RER S	9.04E-06
Petroleum coke, at refinery/RER S	9.90E-06
Nitrogen, liquid, at plant/RER S	2.60E-04
Foam glass, at plant/RER S	9.56E-04
Burning of N2O4/UDMH, O/F = 1.5	2.43E-03
Electricity, production mix RER/RER S	5.13E-03
Chlorine, liquid, production mix, at plant/RER S	5.40E-03
Dimethylamine, at plant/RER S	5.99E-03
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	6.28E-03
Ammonia, liquid, at regional storehouse/RER S	8.94E-03
Metal product manufacturing, average metal working/RER S	2.22E-02
Cobalt, at plant/GLO S	2.46E-02
Polyurethane, rigid foam, at plant/RER S	1.07E-01
Chromium steel product manufacturing, average metal working/RER S	2.09E-01
Steel, electric, chromium steel 18/8, at plant/RER S	3.28E-01
Steel product manufacturing, average metal working/RER S	4.18E-01
Helium, at plant/GLO S	5.22E-01
Aluminium product manufacturing, average metal working/RER S	5.29E-01
Hydrogen, liquid, at plant/RER S	9.97E-01
Aluminium, production mix, wrought alloy, at plant/RER S	1.62E+00
Oxygen, liquid, at plant/RER S	2.20E+00
Molybdenum, at regional storage/RER S	2.28E+00
Electronics for control units/RER S	3.82E+00
Iron-nickel-chromium alloy, at plant/RER S	6.74E+00

Figure 43 shows the same analysis that was performed on the 2 and 3 stage LOX/LH2 rockets above, but this time on a 2 stage LOX/RP1 rocket. Though the life cycle environmental impacts still appear to be dominated by the inert portion of the rocket, the propellants have become proportionally more significant. The production of the fuel, and not just the oxidizer becomes an important influence on the rocket's life cycle impacts.

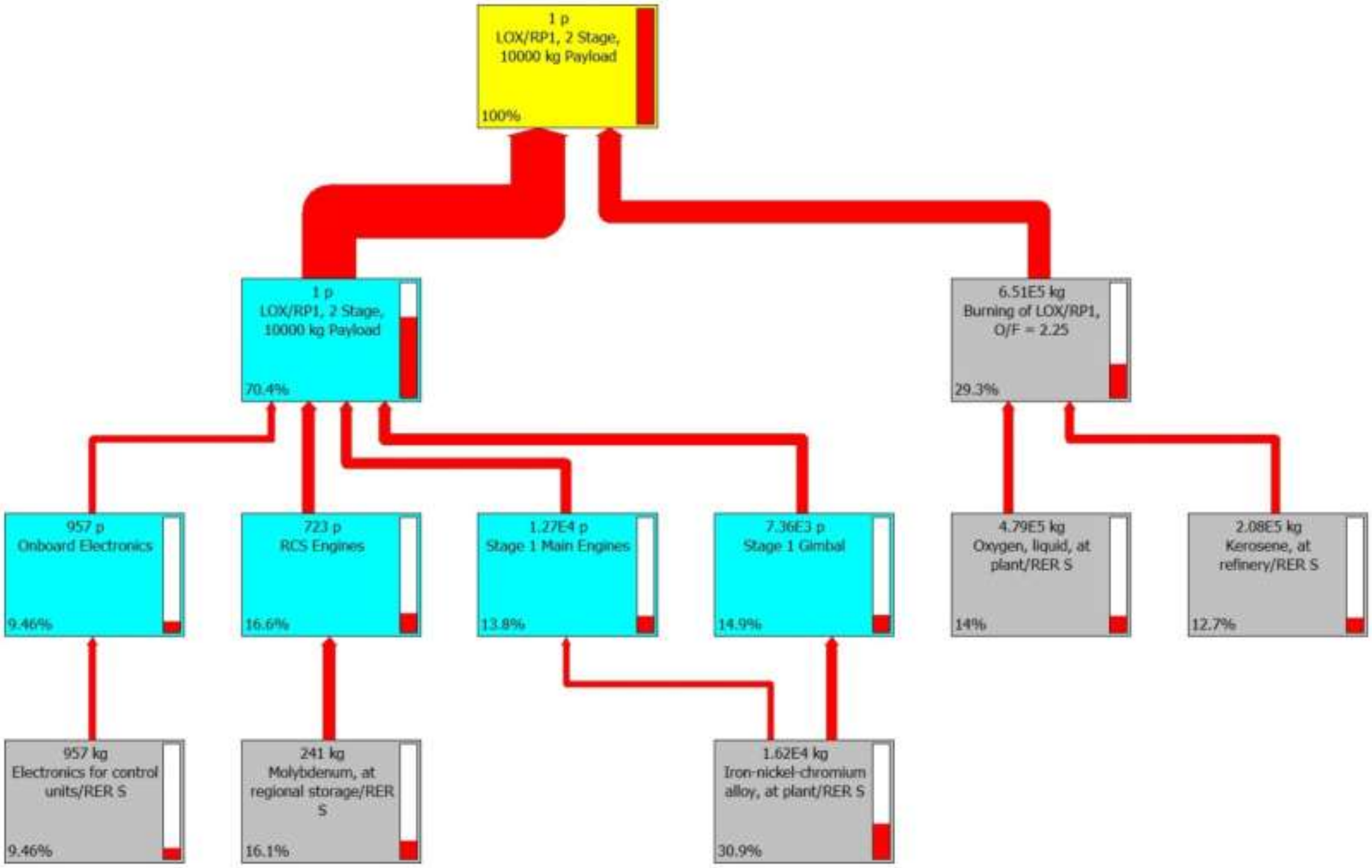


Figure 43: SimaPro LCA results using the ReCiPe 2008 Egalitarian Endpoint single score impact for a 2 stage LOX/RP1 rocket with 10,000 kg to LEO

Table 47: Contribution of each process to the lifetime environmental impacts of a 2 stage, LOX/RP1 rocket capable of 10,000 kg to LEO, with impacts normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint method

Process	Impact (Pt)
Total of all processes	*4.04E+01*
Sodium chloride, powder, at plant/RER S	-1.09E-02
Titanium, Kroll Process, RER	4.99E-07
Argon, liquid, at plant/RER S	3.42E-06
Natural gas, high pressure, at consumer/RER S	1.54E-05
Magnesium, at plant/RER S	2.42E-05
Petroleum coke, at refinery/RER S	2.65E-05
Foam glass, at plant/RER S	8.70E-04
Nitrogen, liquid, at plant/RER S	1.46E-03
Burning of N2O4/UDMH, O/F = 1.5	6.95E-03
Electricity, production mix RER/RER S	2.79E-02
Chlorine, liquid, production mix, at plant/RER S	3.03E-02
Dimethylamine, at plant/RER S	3.36E-02
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	3.53E-02
Ammonia, liquid, at regional storehouse/RER S	5.02E-02
Polyurethane, rigid foam, at plant/RER S	5.71E-02
Metal product manufacturing, average metal working/RER S	6.36E-02
Cobalt, at plant/GLO S	7.03E-02
Chromium steel product manufacturing, average metal working/RER S	3.04E-01
Steel, electric, chromium steel 18/8, at plant/RER S	4.76E-01
Helium, at plant/GLO S	5.51E-01
Aluminium product manufacturing, average metal working/RER S	6.83E-01
Steel product manufacturing, average metal working/RER S	7.75E-01
Burning of LOX/RP1, O/F = 2.25	1.56E+00
Aluminium, production mix, wrought alloy, at plant/RER S	2.09E+00
Electronics for control units/RER S	3.82E+00
Kerosene, at refinery/RER S	5.14E+00
Oxygen, liquid, at plant/RER S	5.65E+00
Molybdenum, at regional storage/RER S	6.51E+00
Iron-nickel-chromium alloy, at plant/RER S	1.25E+01

As with the LOX/LH2 rocket, the 3 stage LOX/RP1 rocket's inert components had a slightly higher impact than the 2 stage LOX/RP1 rocket's inert components. The process tree is shown in Figure 44, while the normalized contributions of each are tabulated in Table 48.

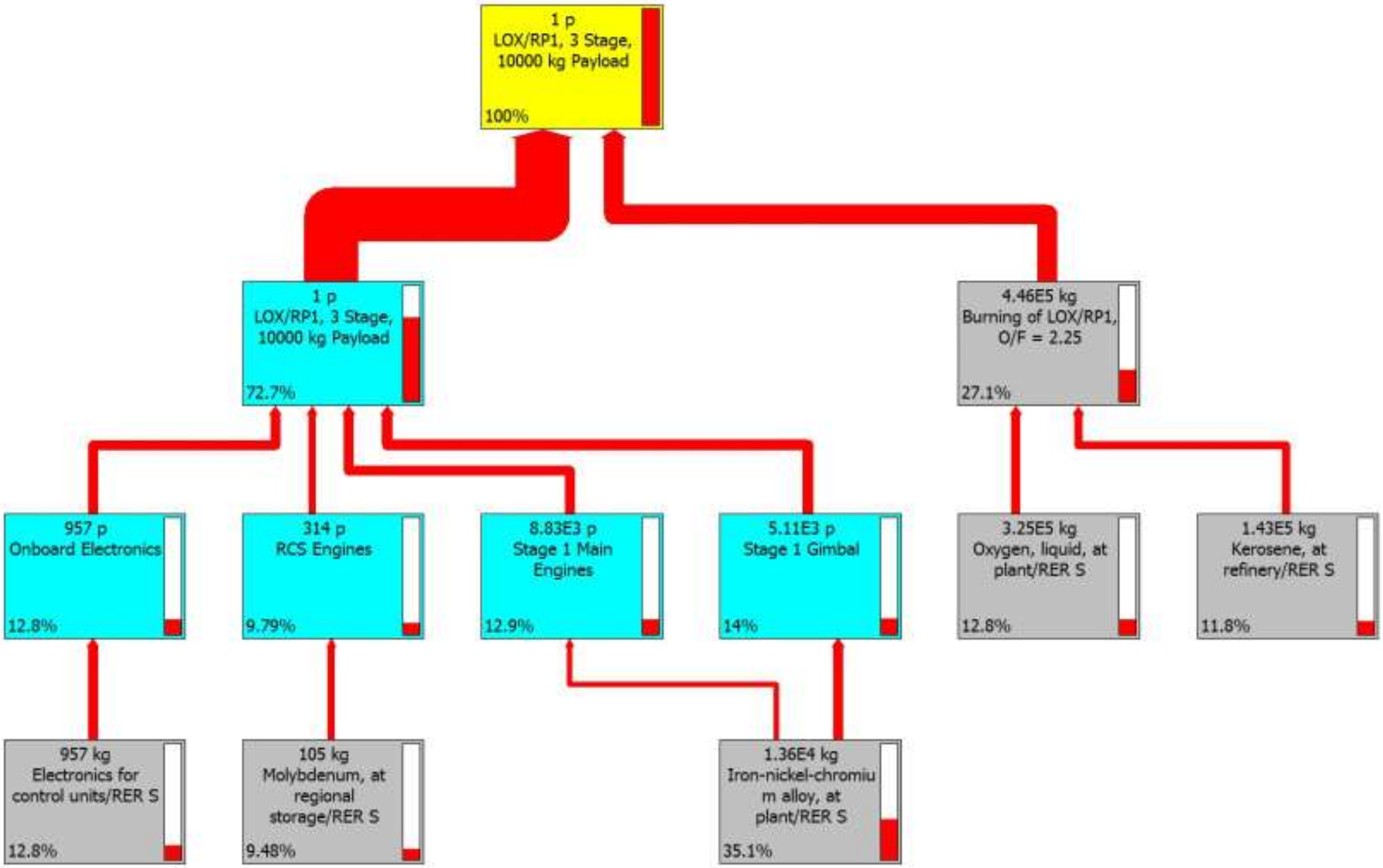


Figure 44: SimaPro LCA results using the ReCiPe 2008 Egalitarian Endpoint single score impact for a 3 stage LOX/RP1 rocket with 10,000 kg to LEO

Table 48: Contribution of each process to the lifetime environmental impacts of a 3 stage, LOX/RP1 rocket capable of 10,000 kg to LEO, with impacts normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint method

Process	Total
Total of all processes	*2.99E+01*
Sodium chloride, powder, at plant/RER S	-2.40E-03
Titanium, Kroll Process, RER	2.28E-07
Argon, liquid, at plant/RER S	1.57E-06
Natural gas, high pressure, at consumer/RER S	7.03E-06
Magnesium, at plant/RER S	1.11E-05
Petroleum coke, at refinery/RER S	1.21E-05
Nitrogen, liquid, at plant/RER S	3.23E-04
Foam glass, at plant/RER S	8.54E-04
Burning of N2O4/UDMH, O/F = 1.5	3.02E-03
Electricity, production mix RER/RER S	6.37E-03
Chlorine, liquid, production mix, at plant/RER S	6.71E-03
Dimethylamine, at plant/RER S	7.44E-03
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	7.81E-03
Ammonia, liquid, at regional storehouse/RER S	1.11E-02
Metal product manufacturing, average metal working/RER S	2.76E-02
Cobalt, at plant/GLO S	3.05E-02
Polyurethane, rigid foam, at plant/RER S	5.85E-02
Chromium steel product manufacturing, average metal working/RER S	2.56E-01
Steel, electric, chromium steel 18/8, at plant/RER S	4.00E-01
Helium, at plant/GLO S	4.42E-01
Aluminium product manufacturing, average metal working/RER S	5.91E-01
Steel product manufacturing, average metal working/RER S	6.50E-01
Burning of LOX/RP1, O/F = 2.25	1.07E+00
Aluminium, production mix, wrought alloy, at plant/RER S	1.81E+00
Molybdenum, at regional storage/RER S	2.83E+00
Kerosene, at refinery/RER S	3.54E+00
Electronics for control units/RER S	3.82E+00
Oxygen, liquid, at plant/RER S	3.83E+00
Iron-nickel-chromium alloy, at plant/RER S	1.05E+01

The process tree for the 2 stage N2O4/UDMH 10,000 kg payload to LEO rocket is shown in Figure 45, with normalized contributions by process tabulated in Table 49. Furthermore, the results from the 3 stage N2O4/UDMH 10,000 kg payload to LEO rocket are shown in Figure 46, while normalized contributions are shown in Table 50.

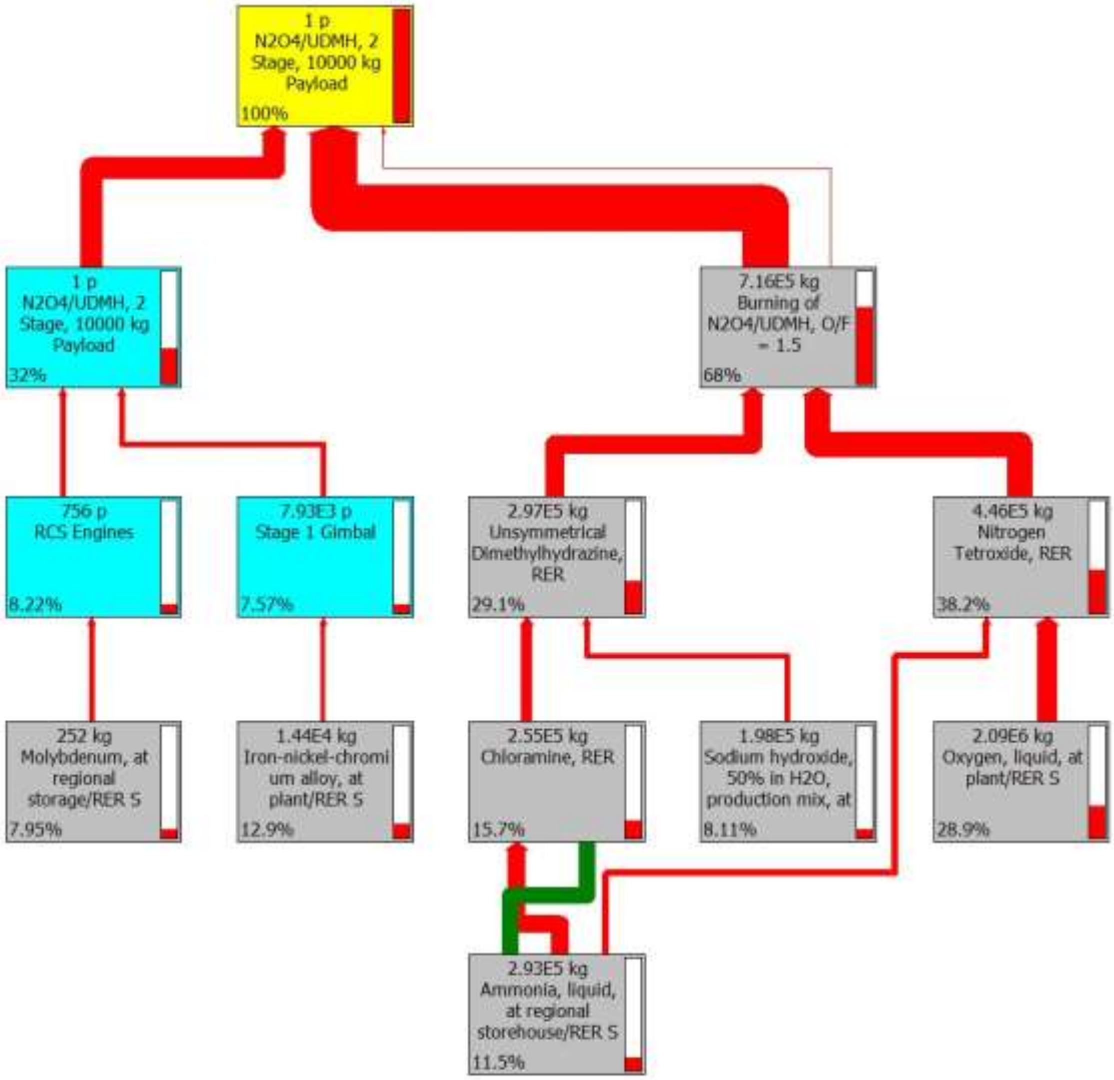


Figure 45: SimaPro LCA results using the ReCiPe 2008 Egalitarian Endpoint single score impact for a 2 stage N2O4/UDMH rocket with 10,000 kg to LEO

Table 49: Contribution of each process to the lifetime environmental impacts of a 2 stage, N2O4/UDMH rocket capable of 10,000 kg to LEO, with impacts normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint method

Process	Impact (Pt)
Total of all processes	*8.56E+01*
Sodium chloride, powder, at plant/RER S	-2.14E+00
Titanium, Kroll Process, RER	5.20E-07
Argon, liquid, at plant/RER S	3.57E-06
Natural gas, high pressure, at consumer/RER S	1.60E-05
Magnesium, at plant/RER S	2.52E-05
Petroleum coke, at refinery/RER S	2.77E-05
Foam glass, at plant/RER S	8.81E-04
Metal product manufacturing, average metal working/RER S	6.64E-02
Cobalt, at plant/GLO S	7.35E-02
Chromium steel product manufacturing, average metal working/RER S	1.38E-01
Steel, electric, chromium steel 18/8, at plant/RER S	2.16E-01
Nitrogen, liquid, at plant/RER S	2.87E-01
Aluminium product manufacturing, average metal working/RER S	4.58E-01
Helium, at plant/GLO S	5.63E-01
Steel product manufacturing, average metal working/RER S	6.87E-01
Aluminium, production mix, wrought alloy, at plant/RER S	1.40E+00
Burning of N2O4/UDMH, O/F = 1.5	2.68E+00
Electronics for control units/RER S	3.82E+00
Electricity, production mix RER/RER S	5.35E+00
Chlorine, liquid, production mix, at plant/RER S	5.95E+00
Dimethylamine, at plant/RER S	6.61E+00
Molybdenum, at regional storage/RER S	6.81E+00
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	6.94E+00
Ammonia, liquid, at regional storehouse/RER S	9.87E+00
Iron-nickel-chromium alloy, at plant/RER S	1.11E+01
Oxygen, liquid, at plant/RER S	2.47E+01

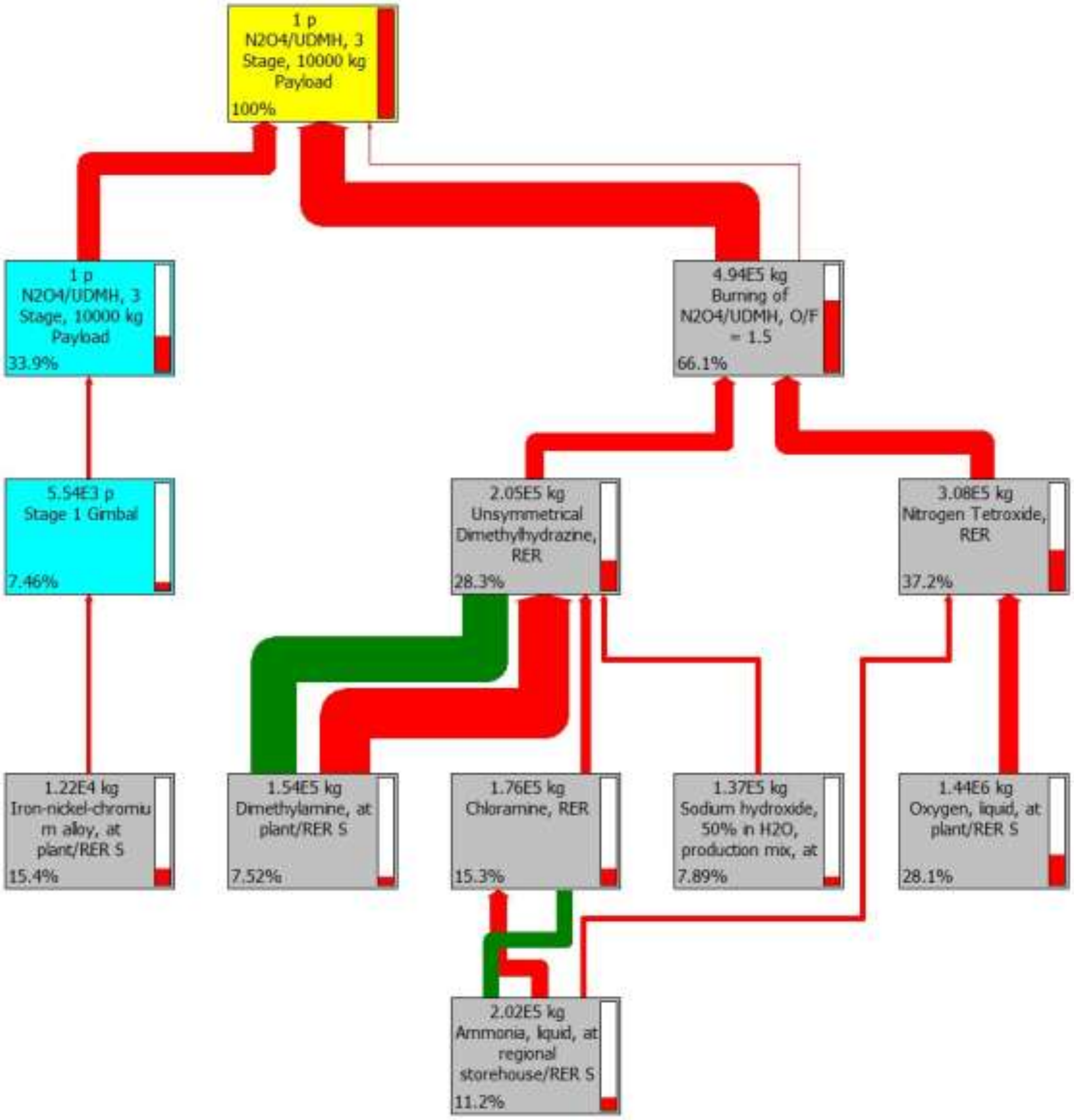


Figure 46: SimaPro LCA results using the ReCiPe 2008 Egalitarian Endpoint single score impact for a 3 stage N2O4/UDMH rocket with 10,000 kg to LEO

Table 50: Contribution of each process to the lifetime environmental impacts of a 3 stage, N2O4/UDMH rocket capable of 10,000 kg to LEO, with impacts normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint method

Process	Total
Total of all processes	*6.07E+01*
Sodium chloride, powder, at plant/RER S	-1.47E+00
Titanium, Kroll Process, RER	2.36E-07
Argon, liquid, at plant/RER S	1.62E-06
Natural gas, high pressure, at consumer/RER S	7.27E-06
Magnesium, at plant/RER S	1.15E-05
Petroleum coke, at refinery/RER S	1.25E-05
Foam glass, at plant/RER S	7.55E-04
Metal product manufacturing, average metal working/RER S	2.86E-02
Cobalt, at plant/GLO S	3.16E-02
Chromium steel product manufacturing, average metal working/RER S	1.21E-01
Steel, electric, chromium steel 18/8, at plant/RER S	1.90E-01
Nitrogen, liquid, at plant/RER S	1.98E-01
Helium, at plant/GLO S	3.88E-01
Aluminium product manufacturing, average metal working/RER S	4.01E-01
Steel product manufacturing, average metal working/RER S	5.81E-01
Aluminium, production mix, wrought alloy, at plant/RER S	1.23E+00
Burning of N2O4/UDMH, O/F = 1.5	1.85E+00
Molybdenum, at regional storage/RER S	2.93E+00
Electricity, production mix RER/RER S	3.69E+00
Electronics for control units/RER S	3.82E+00
Chlorine, liquid, production mix, at plant/RER S	4.11E+00
Dimethylamine, at plant/RER S	4.56E+00
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	4.79E+00
Ammonia, liquid, at regional storehouse/RER S	6.81E+00
Iron-nickel-chromium alloy, at plant/RER S	9.36E+00
Oxygen, liquid, at plant/RER S	1.71E+01

It was expected that the N2O4/UDMH propellant combination would be the most environmentally liquid propellant combination, and this prediction was confirmed by the analysis. Not only did the environmental impacts shift more heavily towards the propellants side of the tree, but the propellants have come to represent the majority of the environmental impacts. Resources consumed during the production of these propellants helped drive the impacts of propellants upwards, surpassing the inert component's impacts.

As with both the LOX/LH2 and LOX/RP1 rockets, the 3 stage N2O4/UDMH rocket's life cycle was impacted slightly more heavily by inert components when compared to the 2 stage rocket. This shift towards the inert components was slight and not enough to surpass the propellant's contribution. It was also found that the overall lifetime impacts of each of the 3 stage rockets is significantly lower than the impacts of the 2 stage rockets with the same payload to LEO. This is discussed further later in this chapter once the effects of light-weighting are introduced.

Finally, a 4 stage solid rocket capable of launching 1,500 kg to LEO was assessed under the same assumptions. The results are shown in Figure 47, with contributions of each process (normalized for 1 kg payload to LEO) tabulated in Table 51.

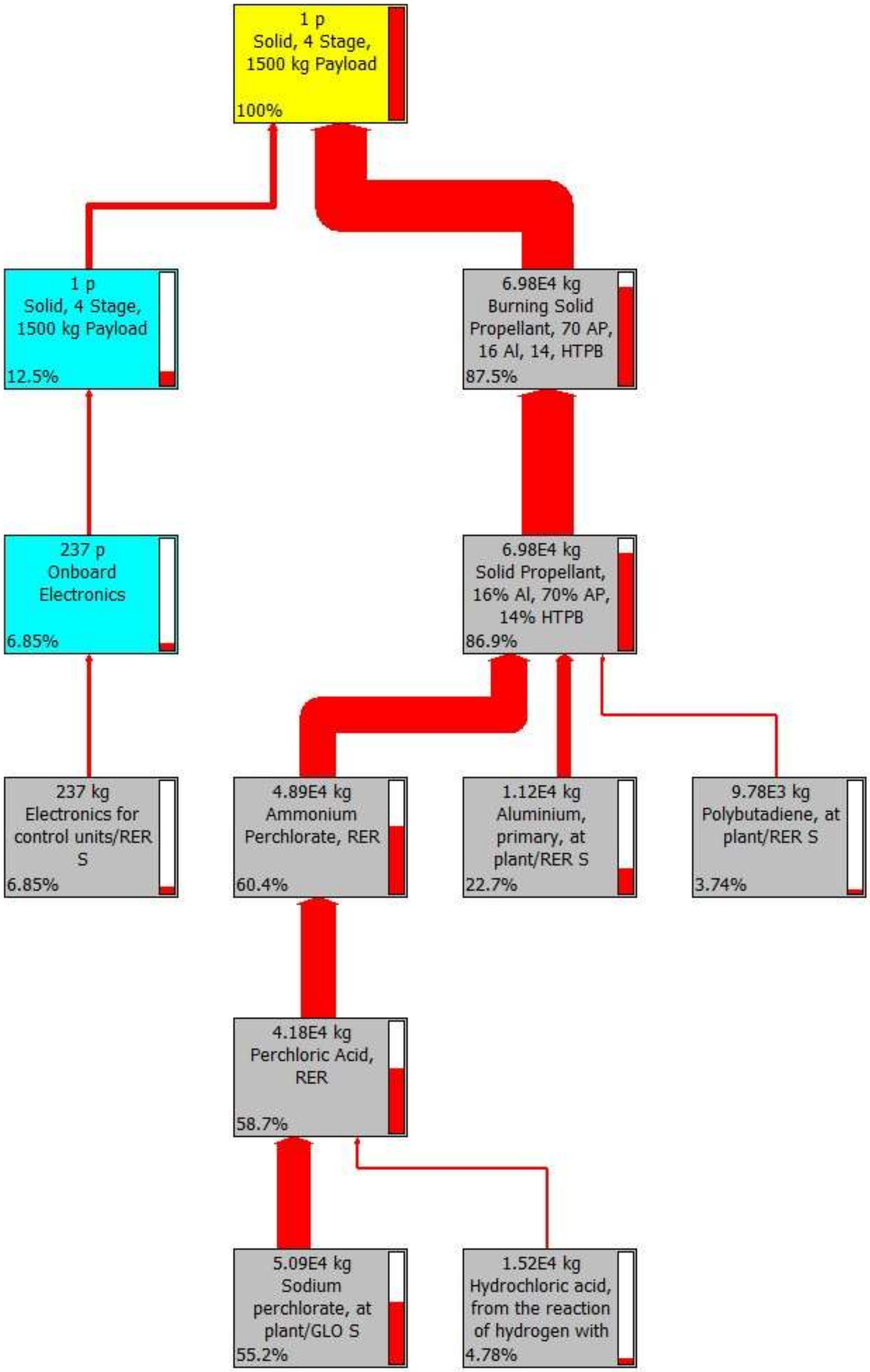


Figure 47: SimaPro LCA results using the ReCiPe 2008 Egalitarian Endpoint single score impact for a 4 stage SOLID rocket with 1,500 kg to LEO

Table 51: Contribution of each process to the lifetime environmental impacts of a 4 stage, SOLIDrocket capable of 1,500 kg to LEO, with impacts normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint method

Process	Impacts (Pt)
Total of all processes	*9.21E+01*
Sodium chloride, powder, at plant/RER S	-1.20E+00
Titanium, Kroll Process, RER	1.94E-07
Argon, liquid, at plant/RER S	1.33E-06
Natural gas, high pressure, at consumer/RER S	5.97E-06
Steel, electric, chromium steel 18/8, at plant/RER S	8.74E-06
Magnesium, at plant/RER S	9.41E-06
Petroleum coke, at refinery/RER S	1.03E-05
Nitrogen, liquid, at plant/RER S	2.39E-04
Helium, at plant/GLO S	4.69E-04
Burning of N2O4/UDMH, O/F = 1.5	2.24E-03
Electricity, production mix RER/RER S	4.76E-03
Chlorine, liquid, production mix, at plant/RER S	4.97E-03
Dimethylamine, at plant/RER S	5.52E-03
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	5.79E-03
Graphite, at plant/RER S	5.81E-03
Explosives, tovex, at plant/CH S	1.01E-02
Metal product manufacturing, average metal working/RER S	2.05E-02
Oxygen, liquid, at plant/RER S	2.06E-02
Cobalt, at plant/GLO S	2.26E-02
Aluminium product manufacturing, average metal working/RER S	1.89E-01
Synthetic rubber, at plant/RER S	4.86E-01
Burning Solid Propellant, 70 AP, 16 Al, 14, HTPB	5.47E-01
Aluminium, production mix, wrought alloy, at plant/RER S	5.78E-01
Steel, low-alloyed, at plant/RER S	8.68E-01
Steel product manufacturing, average metal working/RER S	9.16E-01
Ammonia, liquid, at regional storehouse/RER S	1.60E+00
Molybdenum, at regional storage/RER S	2.10E+00
Polybutadiene, at plant/RER S	3.44E+00
Hydrochloric acid, from the reaction of hydrogen with chlorine, at plant/RER S	4.41E+00
Electronics for control units/RER S	6.31E+00
Aluminium, primary, at plant/RER S	2.09E+01
Sodium perchlorate, at plant/GLO S	5.09E+01

For the solid propellant rocket, life cycle environmental impacts were unquestionably dominated by the propellants and not the inert components of the rocket. This is no surprise given the amount of literature devoted to studying environmental effects specifically of solid propellants. What is surprising is that of the inert components of the rocket, the greatest impact was a result of the onboard electronics, and not any other structural component. This makes sense, though, as electronics are expected to have a relatively high environmental impact and other materials used in the rocket have relatively low environmental burdens (as shown in Section 6.2.6, beginning on page 130).

9.4.2 Life Cycle Environmental Impacts by Impact Category

The following seven tables tabulate the environmental impacts according to each individual impact category of the seven example un-lightened rockets presented in the previous section. Results are shown for both the ReCiPe 2008 Egalitarian Midpoint and the ReCiPe 2008 Egalitarian Endpoint impact assessment methods. All results are normalized for 1 kg of payload to LEO.

Table 52: Environmental impacts according to impact category for the 2 stage LOX/LH2 rocket capable of 10,000 kg to LEO, normalized by 1 kg of payload to LEO, using both the ReCiPe 2008 Egalitarian Midpoint and Endpoint impact assessment methods

Midpoint Indicators			Endpoint Indicators	
Impact Category	**Value**	**Units**	**Impact Category**	**Value (Pts)**
Climate change	3.99E+01	kg CO2 eq	*Total*	*2.38E+01*
Ozone depletion	3.66E-06	kg CFC-11 eq	Climate change Human Health	1.36E+00
Human toxicity	2.61E+03	kg 1,4-DB eq	Ozone depletion	9.20E-05
Photochemical oxidant formation	1.66E-01	kg NMVOC	Human toxicity	1.78E+01
Particulate matter formation	1.72E-01	kg PM10 eq	Photochemical oxidant formation	6.32E-05
Ionising radiation	1.47E+01	kg U235 eq	Particulate matter formation	4.35E-01
Terrestrial acidification	5.88E-01	kg SO2 eq	Ionising radiation	2.34E-03
Freshwater eutrophication	4.52E-02	kg P eq	Climate change Ecosystems	1.11E+00
Marine eutrophication	5.61E-02	kg N eq	Terrestrial acidification	1.25E-02
Terrestrial ecotoxicity	8.87E-02	kg 1,4-DB eq	Freshwater eutrophication	2.97E-03
Freshwater ecotoxicity	1.22E+00	kg 1,4-DB eq	Terrestrial ecotoxicity	1.68E-02
Marine ecotoxicity	1.91E+03	kg 1,4-DB eq	Freshwater ecotoxicity	4.76E-04
Agricultural land occupation	6.29E-01	m2a	Marine ecotoxicity	2.29E-03
Urban land occupation	3.66E-01	m2a	Agricultural land occupation	1.06E-02
Natural land transformation	7.83E-03	m2	Urban land occupation	1.06E-02
Water depletion	3.41E-01	m3	Natural land transformation	5.21E-01
Metal depletion	2.87E+01	kg Fe eq	Metal depletion	1.53E-02
Fossil depletion	2.07E+01	kg oil eq	Fossil depletion	2.48E+00

Table 53: Environmental impacts according to impact category for the 3 stage LOX/LH2 rocket capable of 10,000 kg to LEO, normalized by 1 kg of payload to LEO, using both the ReCiPe 2008 Egalitarian Midpoint and Endpoint impact assessment methods

Midpoint Indicator			Endpoint Indicator	
Impact category	**Value**	**Unit**	**Impact category**	**Value (Pts)**
Climate change	3.40E+01	kg CO2 eq	*Total*	*1.99E+01*
Ozone depletion	3.03E-06	kg CFC-11 eq	Climate change Human Health	1.16E+00
Human toxicity	2.17E+03	kg 1,4-DB eq	Ozone depletion	7.59E-05
Photochemical oxidant formation	1.46E-01	kg NMVOC	Human toxicity	1.48E+01
Particulate matter formation	1.58E-01	kg PM10 eq	Photochemical oxidant formation	5.55E-05
Ionising radiation	1.22E+01	kg U235 eq	Particulate matter formation	4.01E-01
Terrestrial acidification	5.48E-01	kg SO2 eq	Ionising radiation	1.95E-03
Freshwater eutrophication	3.77E-02	kg P eq	Climate change Ecosystems	9.50E-01
Marine eutrophication	4.42E-02	kg N eq	Terrestrial acidification	1.16E-02
Terrestrial ecotoxicity	8.30E-02	kg 1,4-DB eq	Freshwater eutrophication	2.47E-03
Freshwater ecotoxicity	1.08E+00	kg 1,4-DB eq	Terrestrial ecotoxicity	1.58E-02
Marine ecotoxicity	1.66E+03	kg 1,4-DB eq	Freshwater ecotoxicity	4.18E-04
Agricultural land occupation	5.69E-01	m2a	Marine ecotoxicity	1.99E-03
Urban land occupation	3.28E-01	m2a	Agricultural land occupation	9.55E-03
Natural land transformation	6.64E-03	m2	Urban land occupation	9.47E-03
Water depletion	3.01E-01	m3	Natural land transformation	4.68E-01
Metal depletion	2.44E+01	kg Fe eq	Metal depletion	1.30E-02
Fossil depletion	1.66E+01	kg oil eq	Fossil depletion	2.00E+00

Table 54: Environmental impacts according to impact category for the 2 stage LOX/RP1 rocket capable of 10,000 kg to LEO, normalized by 1 kg of payload to LEO, using both the ReCiPe 2008 Egalitarian Midpoint and Endpoint impact assessment methods

Midpoint Indicators			Enpoint Indicators	
Impact category	**Value**	**Unit**	**Impact category**	**Value (Pts)**
Climate change	8.46E+01	kg CO2 eq	*Total*	*4.04E+01*
Ozone depletion	1.40E-05	kg CFC-11 eq	Climate change Human Health	2.89E+00
Human toxicity	4.12E+03	kg 1,4-DB eq	Ozone depletion	3.58E-04
Photochemical oxidant formation	2.96E-01	kg NMVOC	Human toxicity	2.81E+01
Particulate matter formation	3.05E-01	kg PM10 eq	Photochemical oxidant formation	1.13E-04
Ionising radiation	2.54E+01	kg U235 eq	Particulate matter formation	7.73E-01
Terrestrial acidification	1.09E+00	kg SO2 eq	Ionising radiation	4.06E-03
Freshwater eutrophication	7.18E-02	kg P eq	Climate change Ecosystems	2.36E+00
Marine eutrophication	1.11E-01	kg N eq	Terrestrial acidification	2.30E-02
Terrestrial ecotoxicity	1.50E-01	kg 1,4-DB eq	Freshwater eutrophication	4.71E-03
Freshwater ecotoxicity	1.96E+00	kg 1,4-DB eq	Terrestrial ecotoxicity	2.85E-02
Marine ecotoxicity	3.05E+03	kg 1,4-DB eq	Freshwater ecotoxicity	7.63E-04
Agricultural land occupation	9.60E-01	m2a	Marine ecotoxicity	3.64E-03
Urban land occupation	6.36E-01	m2a	Agricultural land occupation	1.61E-02
Natural land transformation	4.81E-02	m2	Urban land occupation	1.83E-02
Water depletion	6.05E-01	m3	Natural land transformation	9.80E-01
Metal depletion	4.46E+01	kg Fe eq	Metal depletion	2.38E-02
Fossil depletion	4.37E+01	kg oil eq	Fossil depletion	5.23E+00

Table 55: Environmental impacts according to impact category for the 3 stage LOX/RP1 rocket capable of 10,000 kg to LEO, normalized by 1 kg of payload to LEO, using both the ReCiPe 2008 Egalitarian Midpoint and Endpoint impact assessment methods

Midpoint Indicators			Endpoint Indicators	
Impact category	**Value**	**Unit**	**Impact category**	**Value (Pts)**
Climate change	6.27E+01	kg CO2 eq	*Total*	*2.99E+01*
Ozone depletion	1.00E-05	kg CFC-11 eq	Climate change Human Health	2.14E+00
Human toxicity	3.04E+03	kg 1,4-DB eq	Ozone depletion	2.55E-04
Photochemical oxidant formation	2.29E-01	kg NMVOC	Human toxicity	2.07E+01
Particulate matter formation	2.45E-01	kg PM10 eq	Photochemical oxidant formation	8.70E-05
Ionising radiation	1.87E+01	kg U235 eq	Particulate matter formation	6.21E-01
Terrestrial acidification	8.78E-01	kg SO2 eq	Ionising radiation	2.99E-03
Freshwater eutrophication	5.30E-02	kg P eq	Climate change Ecosystems	1.75E+00
Marine eutrophication	6.54E-02	kg N eq	Terrestrial acidification	1.86E-02
Terrestrial ecotoxicity	1.22E-01	kg 1,4-DB eq	Freshwater eutrophication	3.48E-03
Freshwater ecotoxicity	1.52E+00	kg 1,4-DB eq	Terrestrial ecotoxicity	2.32E-02
Marine ecotoxicity	2.34E+03	kg 1,4-DB eq	Freshwater ecotoxicity	5.90E-04
Agricultural land occupation	7.71E-01	m2a	Marine ecotoxicity	2.79E-03
Urban land occupation	4.98E-01	m2a	Agricultural land occupation	1.29E-02
Natural land transformation	3.41E-02	m2	Urban land occupation	1.44E-02
Water depletion	4.66E-01	m3	Natural land transformation	7.62E-01
Metal depletion	3.32E+01	kg Fe eq	Metal depletion	1.77E-02
Fossil depletion	3.16E+01	kg oil eq	Fossil depletion	3.79E+00

Table 56: Environmental impacts according to impact category for the 2 stage N2O4/UDMH rocket capable of 10,000 kg to LEO, normalized by 1 kg of payload to LEO, using both the ReCiPe 2008 Egalitarian Midpoint and Endpoint impact assessment methods

Midpoint Indicators			Endpoint Indicators	
Impact category	**Value**	**Unit**	**Impact category**	**Value (Pts)**
Climate change	2.81E+02	kg CO2 eq	*Total*	*8.56E+01*
Ozone depletion	5.34E-05	kg CFC-11 eq	Climate change Human Health	9.61E+00
Human toxicity	7.66E+03	kg 1,4-DB eq	Ozone depletion	1.55E-03
Photochemical oxidant formation	1.61E+00	kg NMVOC	Human toxicity	5.22E+01
Particulate matter formation	7.08E-01	kg PM10 eq	Photochemical oxidant formation	6.12E-04
Ionising radiation	1.25E+02	kg U235 eq	Particulate matter formation	1.79E+00
Terrestrial acidification	2.40E+00	kg SO2 eq	Ionising radiation	2.00E-02
Freshwater eutrophication	1.97E-01	kg P eq	Climate change Ecosystems	7.85E+00
Marine eutrophication	7.48E+00	kg N eq	Terrestrial acidification	5.10E-02
Terrestrial ecotoxicity	3.50E-01	kg 1,4-DB eq	Freshwater eutrophication	1.29E-02
Freshwater ecotoxicity	3.68E+00	kg 1,4-DB eq	Terrestrial ecotoxicity	6.65E-02
Marine ecotoxicity	5.89E+03	kg 1,4-DB eq	Freshwater ecotoxicity	1.43E-03
Agricultural land occupation	3.49E+00	m2a	Marine ecotoxicity	7.04E-03
Urban land occupation	1.15E+00	m2a	Agricultural land occupation	5.84E-02
Natural land transformation	5.85E-02	m2	Urban land occupation	3.32E-02
Water depletion	1.74E+00	m3	Natural land transformation	1.92E+00
Metal depletion	4.42E+01	kg Fe eq	Metal depletion	2.36E-02
Fossil depletion	9.93E+01	kg oil eq	Fossil depletion	1.19E+01

Table 57: Environmental impacts according to impact category for the 3 stage N2O4/UDMH rocket capable of 10,000 kg to LEO, normalized by 1 kg of payload to LEO, using both the ReCiPe 2008 Egalitarian Midpoint and Endpoint impact assessment methods

Midpoint Indicators			**Endpoint Indicators**	
Impact category	**Value**	**Unit**	**Impact category**	**Value (Pts)**
Climate change	1.98E+02	kg CO2 eq	*Total*	*6.07E+01*
Ozone depletion	3.71E-05	kg CFC-11 eq	Climate change Human Health	6.76E+00
Human toxicity	5.45E+03	kg 1,4-DB eq	Ozone depletion	1.08E-03
Photochemical oxidant formation	1.13E+00	kg NMVOC	Human toxicity	3.71E+01
Particulate matter formation	5.19E-01	kg PM10 eq	Photochemical oxidant formation	4.31E-04
Ionising radiation	8.76E+01	kg U235 eq	Particulate matter formation	1.32E+00
Terrestrial acidification	1.78E+00	kg SO2 eq	Ionising radiation	1.40E-02
Freshwater eutrophication	1.39E-01	kg P eq	Climate change Ecosystems	5.52E+00
Marine eutrophication	5.16E+00	kg N eq	Terrestrial acidification	3.77E-02
Terrestrial ecotoxicity	2.58E-01	kg 1,4-DB eq	Freshwater eutrophication	9.12E-03
Freshwater ecotoxicity	2.68E+00	kg 1,4-DB eq	Terrestrial ecotoxicity	4.90E-02
Marine ecotoxicity	4.26E+03	kg 1,4-DB eq	Freshwater ecotoxicity	1.04E-03
Agricultural land occupation	2.51E+00	m2a	Marine ecotoxicity	5.09E-03
Urban land occupation	8.45E-01	m2a	Agricultural land occupation	4.20E-02
Natural land transformation	4.11E-02	m2	Urban land occupation	2.44E-02
Water depletion	1.25E+00	m3	Natural land transformation	1.40E+00
Metal depletion	3.20E+01	kg Fe eq	Metal depletion	1.71E-02
Fossil depletion	6.95E+01	kg oil eq	Fossil depletion	8.35E+00

Table 58: Environmental impacts according to impact category for the 4 stage solid rocket capable of 1,500 kg to LEO, normalized by 1 kg of payload to LEO, using both the ReCiPe 2008 Egalitarian Midpoint and Endpoint impact assessment methods

Midpoint Indicators			**Endpoint Indicators**	
Impact category	**Value**	**Unit**	**Impact category**	**Value (Pts)**
Climate change	3.07E+02	kg CO2 eq	*Total*	*9.21E+01*
Ozone depletion	3.38E-05	kg CFC-11 eq	Climate change Human Health	1.05E+01
Human toxicity	8.43E+03	kg 1,4-DB eq	Ozone depletion	9.61E-04
Photochemical oxidant formation	8.95E-01	kg NMVOC	Human toxicity	5.75E+01
Particulate matter formation	5.96E-01	kg PM10 eq	Photochemical oxidant formation	3.40E-04
Ionising radiation	1.53E+02	kg U235 eq	Particulate matter formation	1.51E+00
Terrestrial acidification	1.84E+00	kg SO2 eq	Ionising radiation	2.44E-02
Freshwater eutrophication	2.32E-01	kg P eq	Climate change Ecosystems	8.58E+00
Marine eutrophication	3.00E-01	kg N eq	Terrestrial acidification	3.90E-02
Terrestrial ecotoxicity	4.18E-01	kg 1,4-DB eq	Freshwater eutrophication	1.52E-02
Freshwater ecotoxicity	4.25E+00	kg 1,4-DB eq	Terrestrial ecotoxicity	7.94E-02
Marine ecotoxicity	6.61E+03	kg 1,4-DB eq	Freshwater ecotoxicity	1.65E-03
Agricultural land occupation	4.61E+00	m2a	Marine ecotoxicity	7.90E-03
Urban land occupation	1.45E+00	m2a	Agricultural land occupation	7.73E-02
Natural land transformation	4.24E-02	m2	Urban land occupation	4.18E-02
Water depletion	6.56E+00	m3	Natural land transformation	2.27E+00
Metal depletion	5.36E+01	kg Fe eq	Metal depletion	2.85E-02
Fossil depletion	9.51E+01	kg oil eq	Fossil depletion	1.14E+01

For each type of rocket, it is seen that the largest environmental impacts come from the human toxicity category, which account for over 50% of the total impacts of the rocket. Toxic chemicals are released into the environment primarily as a result of the metals used in the rocket's structure. These are released as a result of harvesting and refining the metals and during manufacturing processes used to shape the metal into a final product.

The impact categories of fossil depletion, climate change human health, and climate change ecosystems had the second largest contributions to the environmental impacts of the rocket. Combined, these accounted for roughly 30% of each rocket's environmental impacts. These three categories are the result of energy consumption during material harvesting and during manufacturing processes. Fuel is consumed to produce the energy, leading to fossil depletion. Once the fuel is consumed, it releases emissions like carbon dioxide, which lead to climate change.

9.5 Effects of Light-Weighting

9.5.1 <u>The Effect of Light-Weighting on Overall Rocket Size</u>

It is important to note that the values presented in this section may not reflect real world systems perfectly. Their calculation is strongly dependent on the assumptions made about which components can be light-weighted and by how much. Nevertheless, these results are useful in answering the research questions. The important take-away from this section are the *trends* and *relative behavior* of the rocket across different propellants, lift capacities, and number of stages as a result of light-weighting. Real world systems are still expected to behave according to these trends that are being uncovered, even though values may not be exactly representative of the real world system.

It was assumed that when a rocket had certain components light-weighted, the rocket was resized to reflect the change, assuming the payload mass and the ΔV remained constant. This section discusses the effects of light-weighting according to the assumptions made in Section 4.6.4 (beginning on page 87). These assumptions indicate which components are eligible for light-weighting and that light-weighting reduces the mass of a component by 25% of what it would have been if that particular component had not been light-weighted.

For the liquid propelled rockets, it was found that initially reducing the inert mass of the rocket by 1 kg resulted in (on average) an additional 3.95 kg reduction in inert mass and a reduction of about 30.85 kg in propellant load. For the solid propellant rocket, it was found that for every 1 kg the inert mass was initially reduced by, an additional 1.50 kg would be saved from the inert mass and the propellant mass would be reduced by 6.49 kg.

When comparing two liquid propelled rockets with the same lift capacity to LEO and the same propellants, one being the two stage configuration and the other being the three stage configuration, it was found that light-weighting the two stage configuration lead to a greater percent reduction in the overall rocket mass than light-weighting the three stage configuration. This is true for all three liquid propellant combinations under consideration. This is true because the two stage rockets have a lower inert mass fraction, meaning that the ratio of inert mass to propellant mass is lower. The greatest mass savings from light-weighting come from reducing propellant load. Therefore, the rockets with a proportionally higher propellant load have their gross mass reduced by a larger percentage when being light-weighted. These results are shown in Table 59 where it can be seen that light-weighting the three stage configuration of a particular rocket has a leads to a smaller relative reduction in gross mass than light-weighting the two stage configuration of the same rocket.

Table 59: Percent reduction in rocket gross mass due to light-weighting

	Payload to LEO	% Reduction in Gross Mass due to Light-Weighting	
		2 Stage	3 Stage
LOX/LH2	2,500	3.30%	3.18%
	5,000	3.78%	3.66%
	10,000	4.06%	3.95%
	20,000	4.22%	4.12%
	35,000	4.28%	4.19%
	50,000	4.31%	4.22%
	75,000	4.32%	4.24%
	100,000	4.33%	4.25%
	150,000	4.34%	4.26%
	200,000	4.34%	4.27%
LOX/RP1	2,500	3.37%	3.29%
	5,000	3.79%	3.71%
	10,000	4.04%	3.96%
	20,000	4.17%	4.10%
	35,000	4.23%	4.16%
	50,000	4.25%	4.19%
	75,000	4.27%	4.21%
	100,000	4.27%	4.21%
	150,000	4.28%	4.22%
	200,000	4.28%	4.23%
N2O4/UDMH	2,500	3.20%	3.07%
	5,000	3.69%	3.58%
	10,000	3.99%	3.89%
	20,000	4.15%	4.07%
	35,000	4.22%	4.15%
	50,000	4.25%	4.18%
	75,000	4.27%	4.20%
	100,000	4.28%	4.21%
	150,000	4.28%	4.22%
	200,000	4.29%	4.23%

A trend, depicted in Figure 48 with results tabulated in Table 60, was also seen showing that the larger the rocket (larger lift capacity to LEO), the greater the potential reduction in overall size when light-weighted. In other words, light-weighting a rocket with a lift capacity of 2,500 kg to LEO will have a smaller relative reduction in rocket gross mass than light-weighting a similar rocket with a lift capacity of 50,000 kg to LEO. This is due to the same reason light-weighting a two stage rocket has a greater relative reduction in gross mass than light-weighting a similar three stage rocket. The reason is that the inert mass fraction of the rocket decreases as the rocket gets larger. The trend is valid for all propellants, as seen in Figure 48.

What is interesting is that this trend appears to approaches a limit for the liquid propellants. In other words, as the rocket gets larger (greater lift capacity), the relative reduction in gross mass appears to approaches a maximum of about 4.5%. The PRSM was used to model excessively large rockets with lift capacities of 1,000,000,000 kg to LEO. It was found that there was indeed a limit, and it was around 4.3% reduction in gross mass as a result of light-weighting. This limit is unique to the light-weighting assumptions used for these liquid propellants where it was assumed that the mass of only certain components can be reduced by 25% by making the component out of CFRP's. As these assumptions change, the limit shall also change. This is evident when considering the solid propellant rockets.

A different assumption was made when light-weighting the solid rockets. Different components were assumed to be eligible for light-weighting, meaning that a larger fraction of the rocket's structure can be replaced with CFRP's. It appears initially that the gross mass of the solid rockets experiences a greater relative reduction as lift capacity increases, but there does not appear to be a limit. A limit must exist since mass reductions cannot exceed 100%, but the exact limit cannot be determined since the PRSM cannot model solid rockets of excessive size with the MER's used. New MER's must be developed if this limit is to be determined.

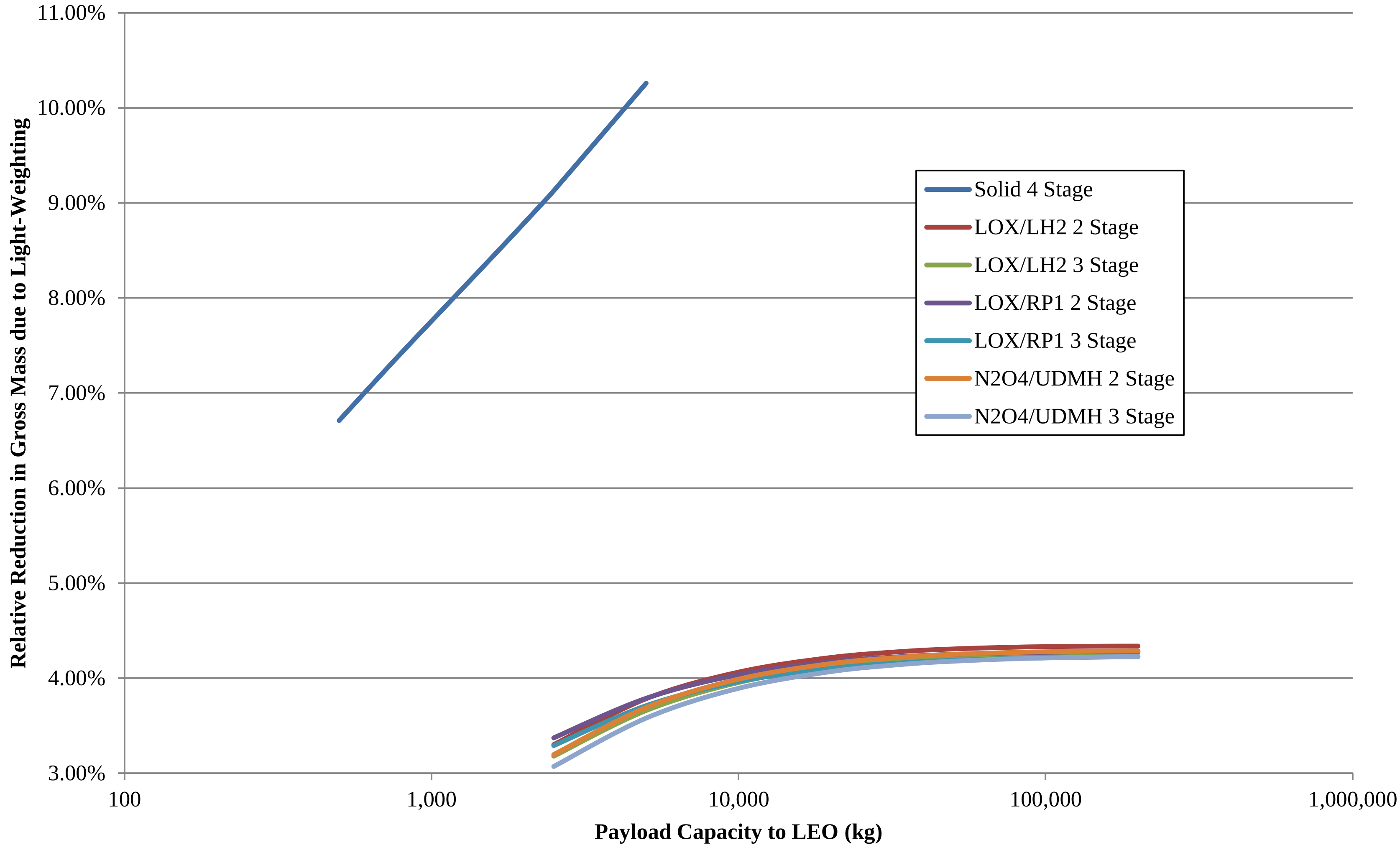


Figure 48: Relative reduction in rocket gross mass as the result of light-weighting

Table 60: Numerical results giving the relative reduction in rocket gross mass as the result of light-weighting

Payload to LEO (kg)	Solid 4 Stage	LOX/LH2 2 Stage	LOX/LH2 3 Stage	LOX/RP1 2 Stage	LOX/RP1 3 Stage	N2O4/UDMH 2 Stage	N2O4/UDMH 3 Stage
500	6.71%	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*
750	7.33%	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*
1,000	7.76%	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*
1,250	8.09%	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*
1,500	8.36%	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*
1,750	8.59%	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*
2,000	8.79%	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*
2,250	8.97%	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*	*(not modeled)*
2,500	9.13%	3.30%	3.18%	3.37%	3.29%	3.20%	3.07%
5,000	10.26%	3.78%	3.66%	3.79%	3.71%	3.69%	3.58%
10,000	*(not modeled)*	4.06%	3.95%	4.04%	3.96%	3.99%	3.89%
20,000	*(not modeled)*	4.22%	4.12%	4.17%	4.10%	4.15%	4.07%
35,000	*(not modeled)*	4.28%	4.19%	4.23%	4.16%	4.22%	4.15%
50,000	*(not modeled)*	4.31%	4.22%	4.25%	4.19%	4.25%	4.18%
75,000	*(not modeled)*	4.32%	4.24%	4.27%	4.21%	4.27%	4.20%
100,000	*(not modeled)*	4.33%	4.25%	4.27%	4.21%	4.28%	4.21%
150,000	*(not modeled)*	4.34%	4.26%	4.28%	4.22%	4.28%	4.22%
200,000	*(not modeled)*	4.34%	4.27%	4.28%	4.23%	4.29%	4.23%

Thus far, the overall reduction in gross mass has been discussed. Table 67 through Table 64 show the reductions broken down into the total reduction in propellant mass and the total reduction in the inert mass of the rocket. These tables were initially presented in Chapter 4, but are repeated here for clarity.

Based on these results, it was found that the LOX/RP1 propelled rockets could expect a greater additional reduction in inert mass, while the N2O4/UDMH rocket could expect a greater reduction in propellant load. The LOX/LH2 experienced the smallest change in both inert and propellant mass when light-weighted.

The most important finding is that when each rocket was light-weighted, the greatest *change* in mass came from the propellants. This is significant because it helps support the prediction that light-weighting reduces environmental impacts by reducing propellant consumption.

Table 61: Final reductions after iterating to resize in inert mass, propellant mass, and gross mass of a rocket after some initial reduction in inert mass due to light-weighting the LOX/LH2 propellant rockets

Payload to LEO (kg)	Stages	Initial Reduction in Inert Mass (kg)	Total Reductions After Iterating		
			Inert Mass (kg)	Propellant Mass (kg)	Gross Mass (kg)
2,500	2	181	794	2,960	3,753
	3	168	643	2,130	2,773
5,000	2	338	1,534	5,803	7,338
	3	318	1,247	4,193	5,440
10,000	2	647	2,980	11,359	14,339
	3	614	2,438	8,268	10,706
20,000	2	1,254	5,831	22,360	28,191
	3	1,197	4,793	16,364	21,156
35,000	2	2,152	10,065	38,740	48,805
	3	2,061	8,297	28,447	36,745
50,000	2	3,040	14,272	55,044	69,316
	3	2,918	11,785	40,494	52,279
75,000	2	4,508	21,250	82,122	103,372
	3	4,338	17,576	60,526	78,102
100,000	2	5,966	28,202	109,124	137,326
	3	5,749	23,350	80,522	103,872
150,000	2	8,860	42,055	162,990	205,045
	3	8,555	34,866	120,448	155,315
200,000	2	11,736	55,866	216,736	272,602
	3	11,347	46,357	160,318	206,675

Table 62: Final reductions after iterating to resize in inert mass, propellant mass, and gross mass of a rocket after some initial reduction in inert mass due to light-weighting the LOX/RP1 propellant rockets

Payload to LEO (kg)	Stages	Initial Reduction in Inert Mass (kg)	Total Reductions After Iterating		
			Inert Mass (kg)	Propellant Mass (kg)	Gross Mass (kg)
2,500	2	169	962	6,726	7,688
	3	156	720	4,468	5,188
5,000	2	321	1,881	13,249	15,130
	3	301	1,416	8,857	10,273
10,000	2	621	3,706	26,218	29,924
	3	587	2,801	17,604	20,404
20,000	2	1,211	7,333	52,048	59,381
	3	1,152	5,558	35,054	40,612
35,000	2	2,085	12,752	90,676	103,428
	3	1,991	9,682	61,184	70,867
50,000	2	2,952	18,158	129,238	147,396
	3	2,825	13,800	87,289	101,089
75,000	2	4,387	27,153	193,428	220,581
	3	4,208	20,654	130,767	151,421
100,000	2	5,813	36,137	257,561	293,698
	3	5,585	27,504	174,223	201,727
150,000	2	8,648	54,087	385,731	439,818
	3	8,326	41,194	261,102	302,296
200,000	2	11,467	72,024	513,830	585,854
	3	11,055	54,879	347,957	402,836

Table 63: Final reductions after iterating to resize in inert mass, propellant mass, and gross mass of a rocket after some initial reduction in inert mass due to light-weighting the N2O4/UDMH propellant rockets

Payload to LEO (kg)	Stages	Initial Reduction in Inert Mass (kg)	Total Reductions After Iterating		
			Inert Mass (kg)	Propellant Mass (kg)	Gross Mass (kg)
2,500	2	171	889	7,212	8,101
	3	158	659	4,820	5,479
5,000	2	323	1,750	14,318	16,068
	3	303	1,302	9,615	10,917
10,000	2	623	3,460	28,418	31,878
	3	589	2,582	19,150	21,732
20,000	2	1,214	6,870	56,573	63,442
	3	1,154	5,138	38,204	43,342
35,000	2	2,090	11,976	98,756	110,732
	3	1,995	8,968	66,771	75,739
50,000	2	2,958	17,078	140,912	157,990
	3	2,831	12,796	95,331	108,126
75,000	2	4,395	25,575	211,146	236,721
	3	4,215	19,175	142,924	162,098
100,000	2	5,824	34,070	281,362	315,432
	3	5,594	25,553	190,514	216,067
150,000	2	8,664	51,056	421,777	472,833
	3	8,339	38,311	285,696	324,007
200,000	2	11,488	68,042	562,188	630,230
	3	11,072	51,070	380,884	431,955

Table 64: Final reductions after iterating to resize in inert mass, propellant mass, and gross mass of a rocket after some initial reduction in inert mass due to light-weighting the solid propellant rockets

Payload to LEO (kg)	Stages	Initial Reduction in Inert Mass (kg)	Total Reductions After Iterating		
			Inert Mass (kg)	Propellant Mass (kg)	Gross Mass (kg)
500	4	257	370	1,677	2,047
750	4	381	558	2,519	3,077
1,000	4	514	761	3,398	4,160
1,250	4	654	978	4,313	5,290
1,500	4	802	1,206	5,258	6,464
1,750	4	955	1,444	6,231	7,676
2,000	4	1,115	1,693	7,230	8,923
2,250	4	1,280	1,950	8,253	10,204
2,500	4	1,449	2,217	9,298	11,515
5,000	4	3,370	5,280	20,759	26,040

9.5.2 Effect of Light-Weighting According to the Single Score Indicator

Seven pairs of rockets, one un-lightened baseline and one light-weighted, each capable of lifting 2,500 kg to LEO were compared to determine how light-weighting reduces environmental impacts. The analysis was performed according to the ReCiPe 2008 Egalitarian Endpoint impact assessment method. Results are shown graphically in Figure 49 and tabulated numerically in Table 65 and Table 66. Though results are only shown for one particular lift capacity, results for different lift capacities are similar.

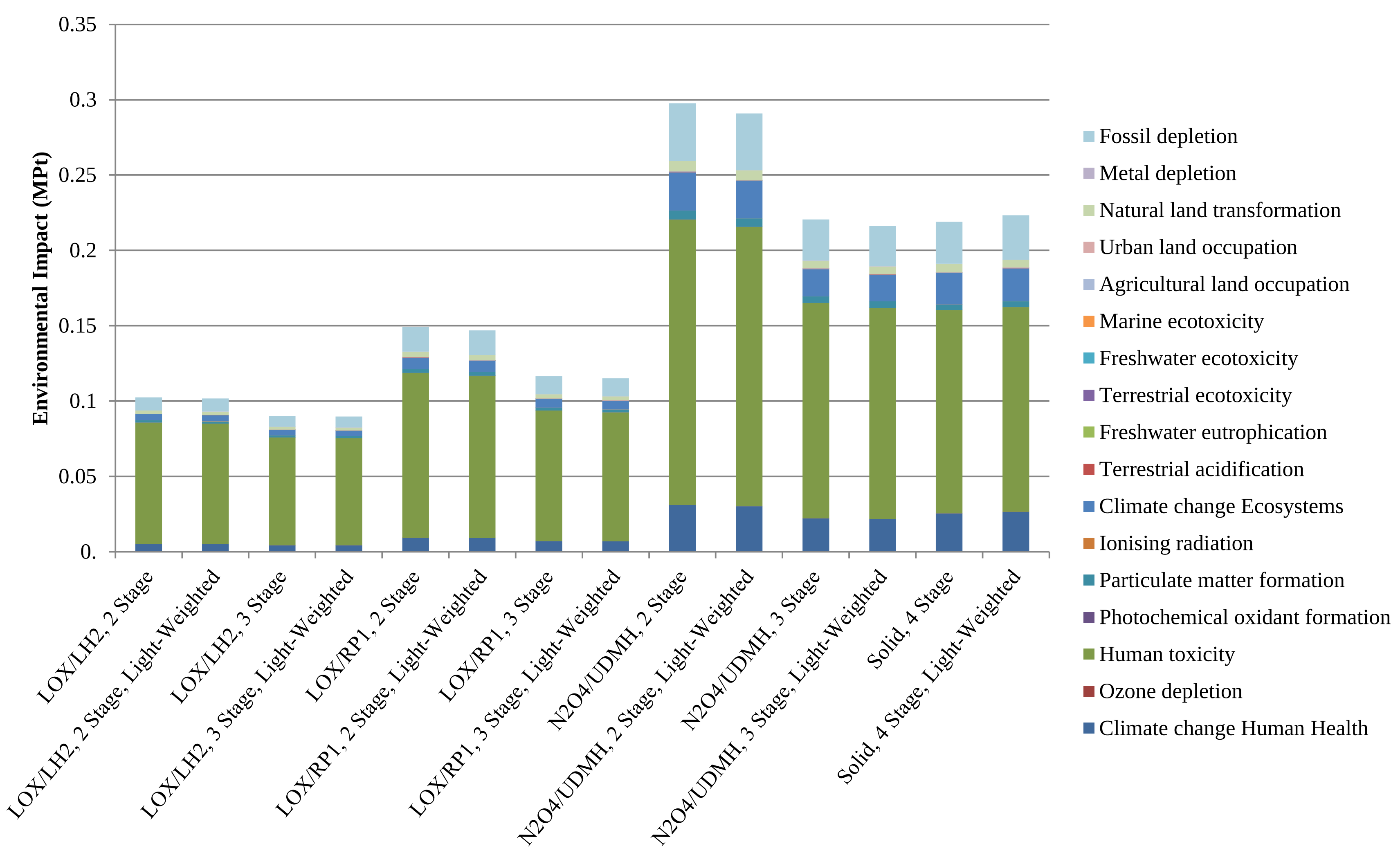


Figure 49: Effects of light-weighting for different rocket configurations, each capable of 2,500 kg to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Table 65: Contribution by impact category when comparing effects of light-weighting for different rocket configurations, each capable of 2,500 kg to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 1)

Configuration	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification
LOX/LH2, 2 Stage	5.00E-03	3.40E-07	8.08E-02	2.30E-07	1.50E-03	8.65E-06	4.00E-03	4.29E-05
LOX/LH2, 2 Stage, Light-Weighted	5.00E-03	3.32E-07	8.00E-02	2.31E-07	1.50E-03	9.48E-06	4.00E-03	4.39E-05
LOX/LH2, 3 Stage	4.30E-03	2.89E-07	7.15E-02	2.07E-07	1.40E-03	7.40E-06	3.50E-03	4.04E-05
LOX/LH2, 3 Stage, Light-Weighted	4.40E-03	2.82E-07	7.10E-02	2.08E-07	1.40E-03	8.14E-06	3.60E-03	4.12E-05
LOX/RP1, 2 Stage	9.40E-03	1.13E-06	1.10E-01	3.68E-07	2.40E-03	1.34E-05	7.60E-03	7.23E-05
LOX/RP1, 2 Stage, Light-Weighted	9.20E-03	1.10E-06	1.08E-01	3.63E-07	2.40E-03	1.40E-05	7.50E-03	7.20E-05
LOX/RP1, 3 Stage	7.00E-03	8.08E-07	8.68E-02	2.87E-07	2.00E-03	1.01E-05	5.70E-03	5.85E-05
LOX/RP1, 3 Stage, Light-Weighted	7.00E-03	7.84E-07	8.56E-02	2.85E-07	1.90E-03	1.07E-05	5.70E-03	5.85E-05
N2O4/UDMH, 2 Stage	3.10E-02	4.96E-06	1.90E-01	1.97E-06	5.80E-03	6.46E-05	2.54E-02	2.00E-04
N2O4/UDMH, 2 Stage, Light-Weighted	3.03E-02	4.81E-06	1.85E-01	1.91E-06	5.60E-03	6.36E-05	2.47E-02	2.00E-04
N2O4/UDMH, 3 Stage	2.22E-02	3.49E-06	1.43E-01	1.40E-06	4.30E-03	4.59E-05	1.81E-02	1.00E-04
N2O4/UDMH, 3 Stage, Light-Weighted	2.17E-02	3.38E-06	1.40E-01	1.37E-06	4.20E-03	4.54E-05	1.77E-02	1.00E-04
Solid, 4 Stage	2.55E-02	2.33E-06	1.35E-01	8.25E-07	3.70E-03	5.94E-05	2.09E-02	9.47E-05
Solid, 4 Stage, Light-Weighted	2.66E-02	2.23E-06	1.36E-01	8.53E-07	3.80E-03	6.44E-05	2.18E-02	1.00E-04

Table 66: Contribution by impact category when comparing effects of light-weighting for different rocket configurations, each capable of 2,500 kg to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 2)

Configuration	Freshwater eutrophication	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
LOX/LH2, 2 Stage	1.29E-05	6.58E-05	1.93E-06	9.48E-06	4.92E-05	4.70E-05	2.20E-03	5.99E-05	8.60E-03
LOX/LH2, 2 Stage, Light-Weighted	1.30E-05	6.23E-05	1.91E-06	9.35E-06	4.96E-05	4.54E-05	2.00E-03	5.83E-05	8.80E-03
LOX/LH2, 3 Stage	1.13E-05	6.28E-05	1.76E-06	8.57E-06	4.61E-05	4.37E-05	2.00E-03	5.28E-05	7.00E-03
LOX/LH2, 3 Stage, Light-Weighted	1.14E-05	5.96E-05	1.73E-06	8.46E-06	4.65E-05	4.23E-05	1.90E-03	5.15E-05	7.20E-03
LOX/RP1, 2 Stage	1.77E-05	9.76E-05	2.72E-06	1.32E-05	6.42E-05	6.88E-05	3.50E-03	8.26E-05	1.66E-02
LOX/RP1, 2 Stage, Light-Weighted	1.76E-05	9.30E-05	2.66E-06	1.29E-05	6.39E-05	6.65E-05	3.40E-03	8.02E-05	1.64E-02
LOX/RP1, 3 Stage	1.39E-05	8.13E-05	2.18E-06	1.06E-05	5.44E-05	5.63E-05	2.80E-03	6.38E-05	1.19E-02
LOX/RP1, 3 Stage, Light-Weighted	1.39E-05	7.75E-05	2.14E-06	1.04E-05	5.43E-05	5.45E-05	2.70E-03	6.20E-05	1.19E-02
N2O4/UDMH, 2 Stage	4.43E-05	2.00E-04	4.95E-06	2.45E-05	2.00E-04	1.00E-04	6.60E-03	8.57E-05	3.84E-02
N2O4/UDMH, 2 Stage, Light-Weighted	4.35E-05	2.00E-04	4.83E-06	2.39E-05	2.00E-04	1.00E-04	6.40E-03	8.34E-05	3.76E-02
N2O4/UDMH, 3 Stage	3.25E-05	2.00E-04	3.75E-06	1.85E-05	1.00E-04	9.15E-05	5.00E-03	6.62E-05	2.73E-02
N2O4/UDMH, 3 Stage, Light-Weighted	3.20E-05	2.00E-04	3.67E-06	1.81E-05	1.00E-04	8.88E-05	4.80E-03	6.46E-05	2.68E-02
Solid, 4 Stage	3.64E-05	2.00E-04	3.95E-06	1.88E-05	2.00E-04	9.98E-05	5.50E-03	6.83E-05	2.78E-02
Solid, 4 Stage, Light-Weighted	3.77E-05	2.00E-04	3.90E-06	1.87E-05	2.00E-04	9.22E-05	5.10E-03	5.35E-05	2.95E-02

For the liquid propellant rockets, it was found that light-weighting reduced lifetime environmental impacts, regardless of propellant combination, lift capacity to LEO, or number of stages. A key item to note is that for each rocket, the greatest *change* in environmental impacts came as a result of the propellants. This was true even for rockets whose life cycles were identified earlier in this chapter to be dominated by the inert parts of the rocket. This confirms the prediction that light-weighting liquid propellant rockets with carbon fiber composites reduces lifetime environmental impacts primarily by reducing propellant requirements.

Looking at individual liquid propellant combinations, it was found that the greatest reduction in lifetime environmental impacts came when light-weighting the N2O4/UDMH rockets, while the smallest reduction in lifetime impacts was seen in the LOX/LH2 rockets. This is not surprising as N2O4/UDMH were seen in Chapter 5 to have the highest impacts of the liquid propellant combinations, while LOX/LH2 had the lowest. Therefore, it is logical that light-weighting would have a relatively greater change in impacts for N2O4/UDMH rockets.

Considering different stages, it was found that the three stage rockets benefited relatively less by light-weighting than their two stage counterparts. Recall that increasing the number of stages increases the inert mass fraction of the rocket, meaning that the ratio of propellants to structure is lower for higher stage rockets. Increased impacts due to replacing structure with relatively higher impact CFRP's are not as significantly offset by reductions in impacts due to a smaller propellant load for three stage rockets as they are for the two stage rockets.

Though the *relative* benefits of light-weighting 3 stage rockets is lower than that of a similar 2 stage rocket, the 3 stage rockets still have an overall smaller environmental impact, as seen in Figure 49. This is an important finding, though not unexpected. Increasing the number of stages a rocket uses during launch means that spent components are shed more regularly. By separating spent components more frequently, a rocket does not have to provide additional thrust or consume additional propellant to lift the useless spent components. This results in an overall smaller propellant load, and thus a smaller overall rocket. Considering the same lift capacity and propellant combination, a smaller rocket naturally has lower environmental impacts than a larger rocket.

However, as the number of stages are increased, the fraction of the rocket's mass that is propellants decreases. This is because of the increased need for inter-stage adapters and other structures required due the added complexity associated with a greater number of stages. Therefore, the relative fraction of the rocket that is structure increases, and thus the relative fraction of the rocket's environmental impacts that are due to the structure is increased.

Next, the solid propellant rockets were considered. Surprisingly, it was found that light-weighting actually *increased* the lifetime environmental impacts of the solid propellant rocket. This is an unexpected outcome, but the reason is clear. The relative amount of a solid rocket's structure that can be replaced with CFRP's was much higher than that of liquid propelled rockets. Furthermore, the difference in impacts between the materials being replaced on the solid rocket and the CFRP's was higher than in the liquid rockets. The dramatic increase in impacts due to structure was not able to be outweighed by reductions in impacts due to reduced propellant load.

The relative reductions in lifetime impacts by rocket configuration are shown in Table 67. The exact amounts change as the total size of the rocket changes, but the pattern is the same, meaning that if Table 67 indicates that there is a reduction in lifetime impacts, then it can be assumed that there is a reduction across all lift capacities for that particular class of rockets.

Table 67: Relative reduction in the lifetime environmental impacts of different rocket configurations, each capable of 2,500 kg to LEO, using the single score indicator

Configuration	Reduction in Lifetime Impacts (%)
LOX/LH2, 2 Stage	0.637%
LOX/LH2, 3 Stage	0.432%
LOX/RP1, 2 Stage	1.619%
LOX/RP1, 3 Stage	1.238%
N2O4/UDMH, 2 Stage	2.310%
N2O4/UDMH, 3 Stage	1.980%
Solid, 4 Stage	-2.057%

9.5.3 Effect of Light-Weighting by Impact Category

There can be tradeoffs when replacing metals with carbon fiber composites. They are different materials and are produced in different ways. Light-weighting with carbon fiber composites does not improve lifetime impacts across every impact category equally. The specific tradeoffs, if any, depend on the specific propellant combination and were found in the LOX/LH2 rockets and the solid propellant rockets. Table 68 compares the baseline and the light-weighted LOX/LH2 rockets showing the ReCiPe 2008 Egalitarian Midpoint indicators by impact category, while tradeoffs are summarized in Table 69.

Table 68: Comparison of environmental impacts by impact category for the two stage LOX/LH2 rocket capable of lifting 10,000 kg to LEO, with results normalized for 1 kg payload to LEO, based on the ReCiPe 2008 Egalitarian Midpoint impact assessment method

Impact category	Unit	Baseline Value	Light-Weighted Value	Difference (%)
Climate change	kg CO2 eq	3.99E+01	4.03E+01	1.00%
Ozone depletion	kg CFC-11 eq	3.66E-06	3.56E-06	-2.73%
Human toxicity	kg 1,4-DB eq	2.61E+03	2.56E+03	-1.92%
Photochemical oxidant formation	kg NMVOC	1.66E-01	1.67E-01	0.60%
Particulate matter formation	kg PM10 eq	1.72E-01	1.70E-01	-1.16%
Ionising radiation	kg U235 eq	1.47E+01	1.65E+01	12.24%
Terrestrial acidification	kg SO2 eq	5.88E-01	6.03E-01	2.55%
Freshwater eutrophication	kg P eq	4.52E-02	4.58E-02	1.33%
Marine eutrophication	kg N eq	5.61E-02	5.81E-02	3.57%
Terrestrial ecotoxicity	kg 1,4-DB eq	8.87E-02	8.17E-02	-7.89%
Freshwater ecotoxicity	kg 1,4-DB eq	1.22E+00	1.20E+00	-1.64%
Marine ecotoxicity	kg 1,4-DB eq	1.91E+03	1.87E+03	-2.09%
Agricultural land occupation	m2a	6.29E-01	6.36E-01	1.11%
Urban land occupation	m2a	3.66E-01	3.46E-01	-5.46%
Natural land transformation	m2	7.83E-03	7.35E-03	-6.13%
Water depletion	m3	3.41E-01	-2.58E+00	-856.60%
Metal depletion	kg Fe eq	2.87E+01	2.76E+01	-3.83%
Fossil depletion	kg oil eq	2.07E+01	2.10E+01	1.45%

Table 69: Tradeoffs seen in the LH2/LOX rockets, showing which impact categories saw an increase in impacts and which saw a decrease after being light-weighted with carbon fiber reinforced polymers

Increased	Decreased
Fossil Depletion	Metal Depletion
Aggricultural Land Occupation	Natural Land Transformation
Marine Eutrophication	Urban Land Occupation
Terrestrial Acidification	Marine Ecotoxicity
Climate Change	Freshwater Ecotoxicity
Ionizing Radiation	Terrestrial Ecotoxicity
Photochemical Oxidant Formation	Particulate Matter Formation
Freshwater Eutrophication	Human Toxicity
	Ozone Depletion
	Water Depletion

Similarly, Table 70 compares the baseline and the light-weighted solid rockets showing the ReCiPe 2008 Egalitarian Midpoint indicators by impact category, while tradeoffs are summarized in Table 71.

Table 70: Comparison of environmental impacts by impact category for the four stage solid rocket capable of lifting 1,500 kg to LEO, with results normalized for 1 kg payload to LEO, based on the ReCiPe 2008 Egalitarian Midpoint impact assessment method

Impact category	Unit	Baseline Value	Light-Weighted Value	Difference (%)
Climate change	kg CO2 eq	3.07E+02	3.19E+02	3.91%
Ozone depletion	kg CFC-11 eq	3.38E-05	3.28E-05	-2.96%
Human toxicity	kg 1,4-DB eq	8.43E+03	8.48E+03	0.59%
Photochemical oxidant formation	kg NMVOC	8.95E-01	9.22E-01	3.02%
Particulate matter formation	kg PM10 eq	5.96E-01	6.15E-01	3.19%
Ionising radiation	kg U235 eq	1.53E+02	1.65E+02	7.84%
Terrestrial acidification	kg SO2 eq	1.84E+00	2.07E+00	12.50%
Freshwater eutrophication	kg P eq	2.32E-01	2.39E-01	3.02%
Marine eutrophication	kg N eq	3.00E-01	3.21E-01	7.00%
Terrestrial ecotoxicity	kg 1,4-DB eq	4.18E-01	3.86E-01	-7.66%
Freshwater ecotoxicity	kg 1,4-DB eq	4.25E+00	4.19E+00	-1.41%
Marine ecotoxicity	kg 1,4-DB eq	6.61E+03	6.56E+03	-0.76%
Agricultural land occupation	m2a	4.61E+00	4.61E+00	0.00%
Urban land occupation	m2a	1.45E+00	1.35E+00	-6.90%
Natural land transformation	m2	4.24E-02	4.12E-02	-2.83%
Water depletion	m3	6.56E+00	-1.60E+01	-343.90%
Metal depletion	kg Fe eq	5.36E+01	4.34E+01	-19.03%
Fossil depletion	kg oil eq	9.51E+01	1.01E+02	6.20%

Table 71: Tradeoffs seen in the solid rockets, showing which impact categories saw an increase in impacts and which saw a decrease after being light-weighted with carbon fiber reinforced polymers

Increased	Decreased
Climate Change	Ozone Depletion
Human Toxicity	Terrestrial Ecotoxicity
Photochemical Oxidant Formation	Freshwater Ecotoxicity
Particulate Matter Formation	Marine Ecotoxicity
Ionising Radiation	Agricultural Land Occupation
Terrestrial Acidification	Urban Land Occupation
Freshwater Eutrophication	Natural Land Transformation
Marine Eutrophication	Water Depletion
Fossil Depletion	Metal Depletion

No or negligible tradeoffs were found in the LOX/RP1 and the N2O4/UDMH rockets. Though light-weighting may not have affected each impact category equally, changes in impacts due to reduction in propellant loads, and thus impact reductions associated with the propellants greatly overshadowed any increases in impacts in certain categories. Results for a LOX/RP1 rocket and an N2O4/UDMH rocket are found in Table 72 and Table 73, respectively.

Table 72: Comparison of environmental impacts by impact category for the two stage LOX/RP1 rocket capable of lifting 10,000 kg to LEO, with results normalized for 1 kg payload to LEO, based on the ReCiPe 2008 Egalitarian Midpoint impact assessment method

Impact category	Unit	Baseline Value	Light-Weighted Value	Difference (%)
Climate change	kg CO2 eq	8.46E+01	8.26E+01	-2.36%
Ozone depletion	kg CFC-11 eq	1.40E-05	1.34E-05	-4.29%
Human toxicity	kg 1,4-DB eq	4.12E+03	4.00E+03	-2.91%
Photochemical oxidant formation	kg NMVOC	2.96E-01	2.90E-01	-2.03%
Particulate matter formation	kg PM10 eq	3.05E-01	2.96E-01	-2.95%
Ionising radiation	kg U235 eq	2.54E+01	2.64E+01	3.94%
Terrestrial acidification	kg SO2 eq	1.09E+00	1.08E+00	-0.92%
Freshwater eutrophication	kg P eq	7.18E-02	7.09E-02	-1.25%
Marine eutrophication	kg N eq	1.11E-01	9.37E-02	-15.59%
Terrestrial ecotoxicity	kg 1,4-DB eq	1.50E-01	1.40E-01	-6.67%
Freshwater ecotoxicity	kg 1,4-DB eq	1.96E+00	1.90E+00	-3.06%
Marine ecotoxicity	kg 1,4-DB eq	3.05E+03	2.95E+03	-3.28%
Agricultural land occupation	m2a	9.60E-01	9.45E-01	-1.56%
Urban land occupation	m2a	6.36E-01	6.03E-01	-5.19%
Natural land transformation	m2	4.81E-02	4.58E-02	-4.78%
Water depletion	m3	6.05E-01	-2.21E+00	-465.29%
Metal depletion	kg Fe eq	4.46E+01	4.27E+01	-4.26%
Fossil depletion	kg oil eq	4.37E+01	4.28E+01	-2.06%

Table 73: Comparison of environmental impacts by impact category for the two stage N2O4/UDMH rocket capable of lifting 10,000 kg to LEO, with results normalized for 1 kg payload to LEO, based on the ReCiPe 2008 Egalitarian Midpoint impact assessment method

Impact category	Unit	Baseline Value	Light-Weighted Value	Difference (%)
Climate change	kg CO2 eq	2.81E+02	2.72E+02	-3.20%
Ozone depletion	kg CFC-11 eq	5.34E-05	5.13E-05	-3.93%
Human toxicity	kg 1,4-DB eq	7.66E+03	7.41E+03	-3.26%
Photochemical oxidant formation	kg NMVOC	1.61E+00	1.55E+00	-3.73%
Particulate matter formation	kg PM10 eq	7.08E-01	6.84E-01	-3.39%
Ionising radiation	kg U235 eq	1.25E+02	1.23E+02	-1.60%
Terrestrial acidification	kg SO2 eq	2.40E+00	2.34E+00	-2.50%
Freshwater eutrophication	kg P eq	1.97E-01	1.91E-01	-3.05%
Marine eutrophication	kg N eq	7.48E+00	7.19E+00	-3.88%
Terrestrial ecotoxicity	kg 1,4-DB eq	3.50E-01	3.33E-01	-4.86%
Freshwater ecotoxicity	kg 1,4-DB eq	3.68E+00	3.56E+00	-3.26%
Marine ecotoxicity	kg 1,4-DB eq	5.89E+03	5.69E+03	-3.40%
Agricultural land occupation	m2a	3.49E+00	3.38E+00	-3.15%
Urban land occupation	m2a	1.15E+00	1.10E+00	-4.35%
Natural land transformation	m2	5.85E-02	5.60E-02	-4.27%
Water depletion	m3	1.74E+00	-1.12E+00	-164.37%
Metal depletion	kg Fe eq	4.42E+01	4.24E+01	-4.07%
Fossil depletion	kg oil eq	9.93E+01	9.64E+01	-2.92%

9.5.4 General Conclusion About Light-Weighting

The final conclusions about light-weighting and the way in which these conclusions fit into the bigger picture of this research are discussed in detail in Chapter 12. Nevertheless, this section provides an overview of some trends and relationships that were seen in the analysis.

9.6 Normalizing Results by the Functional Unit

First, rockets of the same propellant combinations and number of stages, but different lift capacities were compared to each other. Each rocket's total lifetime environmental impacts were normalized by 1 kg of payload to LEO. The results for the two stage LH2/LOX rockets are shown in Figure 50. Results for each of the other rocket configurations, both baseline and light-weighted, were similar and can be found in Appendix C.

The smallest rockets have the largest impact per kilogram to LEO. This is because the onboard electronics, which are an environmentally burdensome component, account for a larger percentage of the rockets total mass. There also seems to be limiting behavior. As the rockets get larger, the potential benefit of increasing rocket size gets smaller.

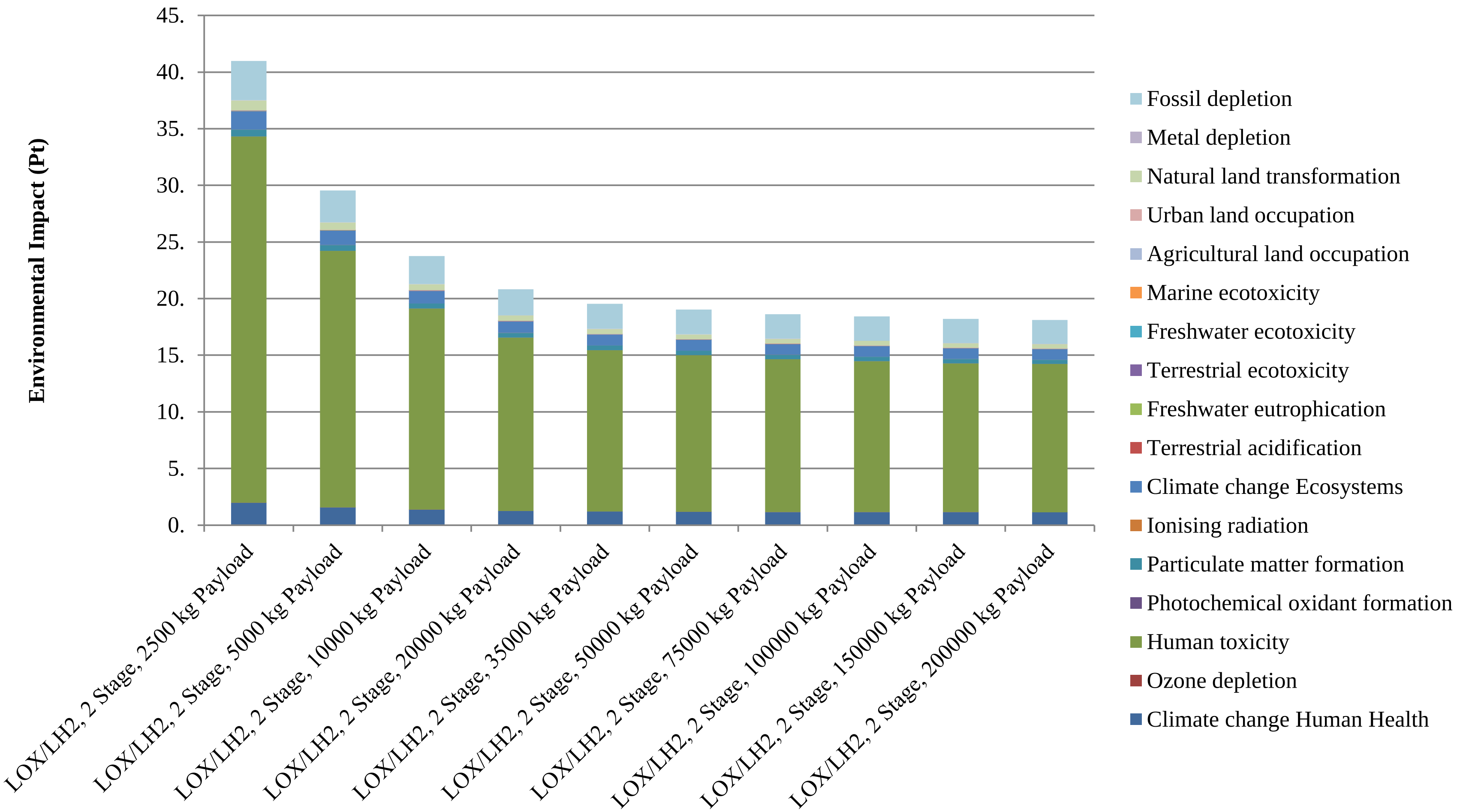


Figure 50: Environmental impact per kilogram of payload to LEO for the two stage LOX/LH2 rockets, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Table 74: Contributions by impact category to the environmental impacts of lifting 1 kg of payload to LEO using two stage, LOX/LH2 rockets (Part 1)

Configuration	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification
LOX/LH2, 2 Stage, 2500 kg Payload, LW	2.00E+00	1.00E-04	3.20E+01	9.26E-05	5.96E-01	3.80E-03	1.64E+00	1.75E-02
LOX/LH2, 2 Stage, 5000 kg Payload, LW	1.59E+00	1.00E-04	2.23E+01	7.33E-05	4.86E-01	3.00E-03	1.30E+00	1.44E-02
LOX/LH2, 2 Stage, 10000 kg Payload, LW	1.38E+00	8.89E-05	1.75E+01	6.34E-05	4.29E-01	2.60E-03	1.13E+00	1.28E-02
LOX/LH2, 2 Stage, 20000 kg Payload, LW	1.27E+00	8.13E-05	1.50E+01	5.82E-05	4.00E-01	2.40E-03	1.03E+00	1.20E-02
LOX/LH2, 2 Stage, 35000 kg Payload, LW	1.21E+00	7.79E-05	1.39E+01	5.59E-05	3.88E-01	2.30E-03	9.92E-01	1.16E-02
LOX/LH2, 2 Stage, 50000 kg Payload, LW	1.19E+00	7.65E-05	1.35E+01	5.50E-05	3.83E-01	2.30E-03	9.74E-01	1.15E-02
LOX/LH2, 2 Stage, 75000 kg Payload, LW	1.17E+00	7.53E-05	1.32E+01	5.42E-05	3.79E-01	2.30E-03	9.59E-01	1.14E-02
LOX/LH2, 2 Stage, 100000 kg Payload, LW	1.16E+00	7.47E-05	1.30E+01	5.38E-05	3.77E-01	2.20E-03	9.52E-01	1.13E-02
LOX/LH2, 2 Stage, 150000 kg Payload, LW	1.15E+00	7.40E-05	1.28E+01	5.34E-05	3.75E-01	2.20E-03	9.42E-01	1.13E-02
LOX/LH2, 2 Stage, 200000 kg Payload, LW	1.15E+00	7.38E-05	1.28E+01	5.32E-05	3.75E-01	2.20E-03	9.39E-01	1.13E-02

Table 75: Contributions by impact category to the environmental impacts of lifting 1 kg of payload to LEO using two stage, LOX/LH2 rockets (Part 2)

Configuration	Freshwater eutrophication	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
LOX/LH2, 2 Stage, 2500 kg Payload, LW	5.20E-03	2.49E-02	8.00E-04	3.70E-03	1.98E-02	1.82E-02	8.38E-01	2.33E-02	3.50E+00
LOX/LH2, 2 Stage, 5000 kg Payload, LW	3.70E-03	1.87E-02	6.00E-04	2.70E-03	1.37E-02	1.27E-02	6.10E-01	1.76E-02	2.85E+00
LOX/LH2, 2 Stage, 10000 kg Payload, LW	3.00E-03	1.55E-02	5.00E-04	2.20E-03	1.07E-02	1.00E-02	4.95E-01	1.47E-02	2.52E+00
LOX/LH2, 2 Stage, 20000 kg Payload, LW	2.60E-03	1.39E-02	4.00E-04	2.00E-03	9.10E-03	8.60E-03	4.37E-01	1.32E-02	2.34E+00
LOX/LH2, 2 Stage, 35000 kg Payload, LW	2.50E-03	1.32E-02	4.00E-04	1.90E-03	8.40E-03	8.00E-03	4.12E-01	1.26E-02	2.26E+00
LOX/LH2, 2 Stage, 50000 kg Payload, LW	2.40E-03	1.30E-02	4.00E-04	1.80E-03	8.10E-03	7.80E-03	4.02E-01	1.24E-02	2.22E+00
LOX/LH2, 2 Stage, 75000 kg Payload, LW	2.40E-03	1.27E-02	4.00E-04	1.80E-03	7.90E-03	7.60E-03	3.94E-01	1.22E-02	2.19E+00
LOX/LH2, 2 Stage, 100000 kg Payload, LW	2.30E-03	1.26E-02	4.00E-04	1.80E-03	7.80E-03	7.50E-03	3.90E-01	1.20E-02	2.18E+00
LOX/LH2, 2 Stage, 150000 kg Payload, LW	2.30E-03	1.25E-02	4.00E-04	1.80E-03	7.70E-03	7.40E-03	3.85E-01	1.20E-02	2.16E+00
LOX/LH2, 2 Stage, 200000 kg Payload, LW	2.30E-03	1.25E-02	4.00E-04	1.70E-03	7.60E-03	7.30E-03	3.84E-01	1.19E-02	2.15E+00

The lifetime environmental impacts of getting 1 kg of payload to LEO for each of the rockets considered are summarized in Table 76.

Table 76: Comparison of environmental impacts of lifting 1 kg of payload to LEO, using the single score indicator. The largest rocket of each configuration was used, establishing a lower limit

Propellants	Stages	Environmental Impact (Pt)		Difference (%)
		Baseline	Light-Weighted	
LOX/LH2	2	18.12	17.81	1.70%
	3	14.65	14.47	1.23%
LOX/RP1	2	34.45	33.32	3.30%
	3	24.57	23.97	2.46%
N2O4/UDMH	2	75.76	72.98	3.67%
	3	52.44	50.66	3.40%
Solid	4	85.86	88.18	-2.69%

It is clear that light-weighting has a benefit, though small, for each of the liquid propellant rockets. The benefit depends on the propellants being consumed and is greatest for the N2O4/UDMH rockets and smallest for the LOX/LH2 rockets. This is expected as N2O4/UDMH was found to be the most burdensome of the propellants, while LOX/LH2 was the least burdensome. The increase in environmental burdens of light-weighting the solid rocket is also evident.

According to these results, given a particular propellant combination, the environmental benefit of increasing the number of stages is greater than the benefit of light-weighting the same rocket. This is because increasing number of stages reduces required propellants more than light-weighting the same rocket.

Results for all configurations according to impact category are found in Appendix C.

9.7 Chapter Summary

It was found that the LOX/LH2 and the LOX/RP1 rockets' life cycle environmental impacts are dominated by their inert components, while the N2O4/UDMH and the solid propellant rockets have their life cycles dominated by their propellants. Looking at each individual stage of life, all rockets were found to be dominated by the material harvesting phases of life, with manufacturing representing a slightly smaller impact. It was found that burning the propellants in the atmosphere is a small fraction of the rocket's life cycle impacts. Disposal of spent rocket stages was found to be extremely small and negligible.

Based on the analysis, it is found that light-weighting the liquid propelled rockets decreases environmental burdens. The relative benefit is a function of the propellant combination chosen. For the solid rocket, it was found that light-weighting increases environmental burdens. Increasing number of stages was found to have a greater benefit to the environment than light-weighting.

Additional discussion of these results and what they mean in terms of answering the research questions is found in Chapter 12.

10 UNCERTAINTY ANALYSIS

10.1 Purpose of the Uncertainty Analysis

The PRSM and the LCA model are not expected to be a high fidelity representation of real world systems. However, it is important to determine the level of confidence to which the conclusion is drawn that light-weighting is environmentally preferable. The uncertainty analysis assumes that there is some percent error in the results from the PRSM and the data used in the LCA when compared to what may actually be experienced by a real world rocket. Assigning different levels of uncertainty to each of these numbers can be used to gage how confidently it can be concluded that light-weighting of rockets with CFRP's is environmentally beneficial.

Error bounds were applied to values in each component of the rocket. Specifying an error of some percent, like ±10%, indicates that a 1 kg component may, in fact, be as light as 0.9 kg or as heavy as 1.1 kg, accounting for errors caused in the PRSM. Likewise, processes like manufacturing processes were assigned this amount of uncertainty, saying that the process may produce 10% fewer or more environmental burdens, accounting for potential errors found in data. An even distribution was assumed within the range of uncertainty so that values closer to the median would not be disproportionately represented.

Three different levels of uncertainty were assumed: low, moderate, and high. The assumed percent error in these three levels of uncertainty is based on the results obtained by comparing the results from the PRSM to real world systems in Section 4.7 (beginning on page 93). For the low level of uncertainty, it is assumed that the PRSM and data used in the LCA model are off by up to ±10% from actual, real world numbers. For the medium level error, it was assumed that the PRSM and data used in the LCA model are off by up to ±25% from actual, real world numbers. The high level of error assumes that the PRSM and data used in the LCA can be off by as much as ±50% when compared to real world numbers.

An uncertainty of ±10% assumes that the data used is fairly accurate and that the PRSM and the LCA model reflect real world systems rather accurately. A ±25% error means that the PRSM and the LCA model are believed to have done a decently good job and reflects the performance of real world systems relatively well, though some improvement may be necessary. The high uncertainty of ±50% reflects significant deviations from modeled results and real world results.

For each level of uncertainty, a Monte Carlo simulation is run to determine whether there is some combination of errors that can contradict the conclusion that light-weighting of rockets is environmentally beneficial, and if so, how likely is it to be the case. Each simulation runs 10,000 scenarios, ensuring a large sample size and good distribution.

The results from this analysis are found in the following sections.

10.2 Low Uncertainty (±10%)

An error of ±10% was assigned according to the method described in the previous section. The lifetime environmental impacts of a baseline rocket of a particular configuration were compared to the light-weighted version of the same configuration.

The results for the low uncertainty analysis comparing a baseline and a light-weighted two stage, 10,000 kg to LEO, LOX/LH2 rocket are shown in Figure 51. This figure plots the probability density function of the difference in lifetime environmental impacts (single score indicator, in Pts) between the baseline rocket and the light-weighted rocket of the same configuration. Positive values indicate that the baseline rocket has higher environmental impacts than the light-weighted rocket, while negative values indicate that the light-weighted rocket is worse for the environment. After 10,000 runs, it was found that the light-weighted rocket always had a smaller environmental impact overall.

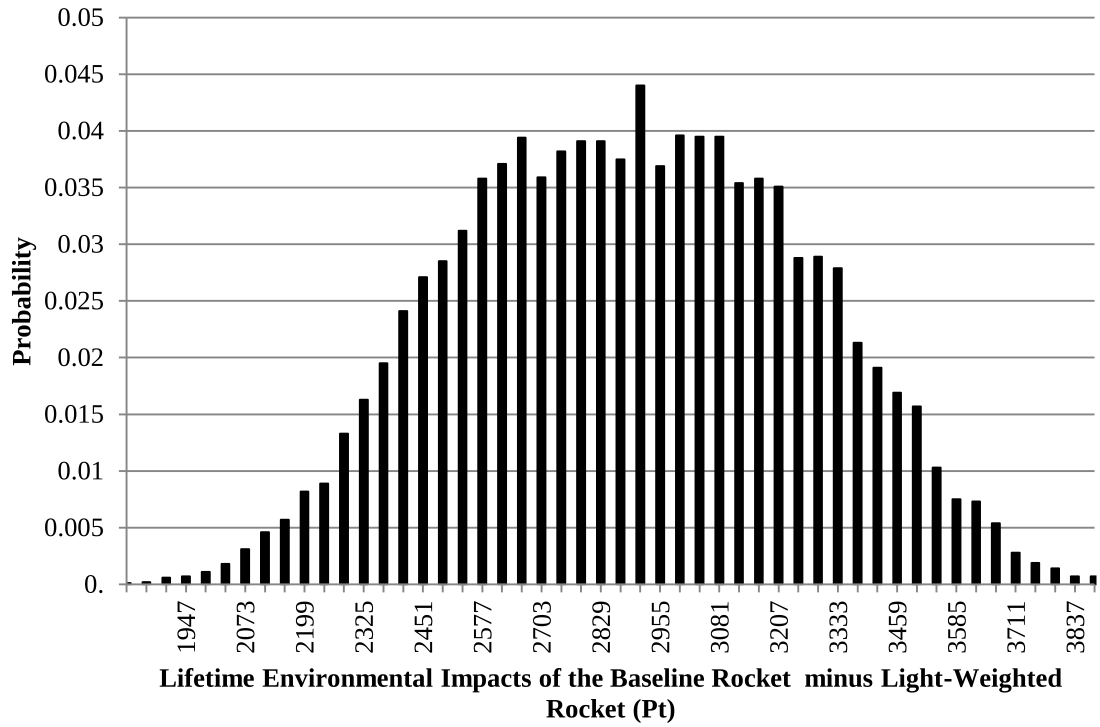


Figure 51: Probability density function showing the results from the low uncertainty analysis on the two stage, 10,000 kg to LEO, LOX/LH2 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Similar results were obtained for the three stage LOX/LH2 rocket, as well as each of the LOX/RP1 rockets and N2O4/UDMH rockets. In each case, it was found that the baseline rocket always had a higher environmental impact than the light-weighted rocket.

The probability density functions showing these results for the LOX/RP1 and the N2O4/UDMH rockets can be found in Appendix E.

Looking at individual impact categories, the tradeoffs discussed in Chapter 9 between impact categories for the LOX/LH2 rocket can clearly be seen. These tradeoffs exist because the environmental impacts of using CFRP's are different than those of using metals, meaning that changing materials changes impacts on the environment. Tradeoffs exist for the LOX/LH2 rocket because the propellants have a relatively low contribution to the lifetime environmental impacts, which are most sensitive to changes in structural material. Similar to the purpose of the single score indicator analysis, the uncertainty analysis determines the likelihood that certain tradeoffs occur when CFRP's are used.

The likelihood of tradeoffs occuring is shown in Figure 52. The bar shown for each impact category sums to 100%. The further the bar is to the left (towards -100) the more likely it is that the impacts of the baseline rocket are lower than those of the light-weighted rocket in that impact category, indicating that light-weighting with CFRP's is worse for the environment in that particular category. Likewise, a shift to the right (towards 100) indicates that light-weighting is an improvement in the category. If the bar is split, then it indicates that there are some cases where light-weighting is an improvement, and some where it is not. The bar indicates the relative fraction of cases, out of the 10,000 simulations that were run, that light-weighting was better or worse.

It can be seen that light-weighting a LOX/LH2 rocket is always environmentally beneficial in certain impact categories and always detrimental in other categories. In the case of photochemical oxidant formation, light-weighting is likely worse, but there are certain extreme situations where it can reduce the rockets impacts in this category.

Photochemical oxidant formation is measured in units of equivalent kilograms of non-methane volatile organic compounds (VOC's). When using CFRP's this impact category can get worse for the environment since the production of carbon fibers and the use of epoxy resins release VOC's. These VOC's can also be produced while consuming fuel for energy production during many metal processing steps, and the amount of VOC's released during CFRP processes is not significantly higher than when using and working with metals. At the extreme cases of uncertainty, when it is assumed that the data used *over* estimated the impacts of using carbon fibers, it is possible that CFRP's in fact release fewer VOC's.

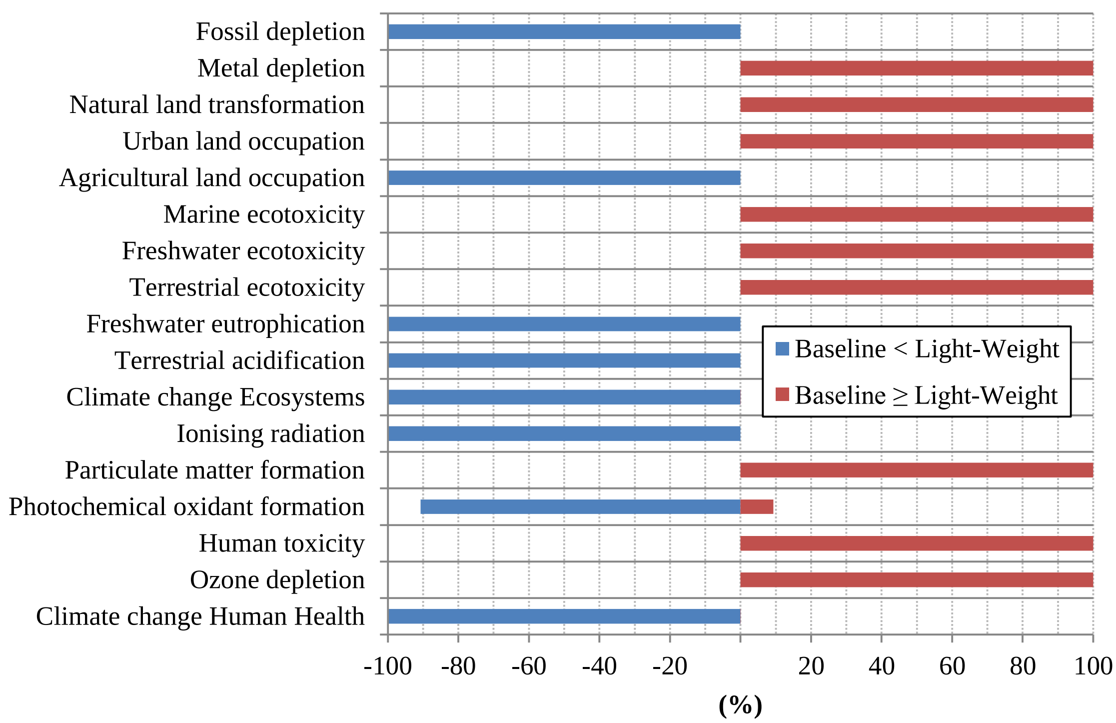


Figure 52: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, LOX/LH2 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Though light-weighting was found to improve environmental impacts according to the single score indicator, the specific categories that saw an improvement depended on the propellant combination. The LH2/LOX rocket experienced multiple tradeoffs (as discussed and shown earlier), while the LOX/RP1 and the N2O4/UDMH rockets saw an improvement across all categories. This is because the life cycles of the LOX/RP1 and N2O4/UDMH rockets were more heavily influenced by the production and consumption of propellants, making them more sensitive to uncertainty with propellants and not structures. Since using less of the same propellants is always an improvement, these rocket configurations always showed that light-weighting was better for the environment.

When considering three stages, instead of two, it is found that results tend to shift towards there being more tradeoffs amongst categories, though the single score indicator still suggests that light-weighting is still better overall. This shift is due to the impacts of structures becoming relatively more important. According to (Humble, Henry et al. 1995), it is expected that increasing the number of stages increases the inert mass fraction of the rocket, as is found to be the case in the results from the PRSM. This means the relative mass of the structure is higher in rockets of greater number of stages than in rockets of fewer stages. It is seen in the results in Chapter 9 that increasing number of stages increases the relative impacts of structures, putting more emphasis on the difference between carbon fiber composites and the metals they are replacing.

As discussed in Chapter 9, it was found that light-weighting rockets that use solid propellants always increased lifetime environmental impacts. This was not expected, so it is even more important to perform an uncertainty analysis on this particular configuration. This uncertainty analysis makes sure that this research didn’t, by chance, pick a particular rocket configuration that would always increase impacts when light-weighted.

The results from an uncertainty analysis on a 1,500 kg, four stage, solid propellant rocket are shown in the probability density function shown in Figure 53. As before, these results show the difference in single score impacts between the baseline rocket and the light-weighted rocket on the horizontal axis, and the probability of this result on the vertical axis. It is seen that the difference in burdens is always negative, meaning that light-weighting is always worse for the environment according to the single score indicator.

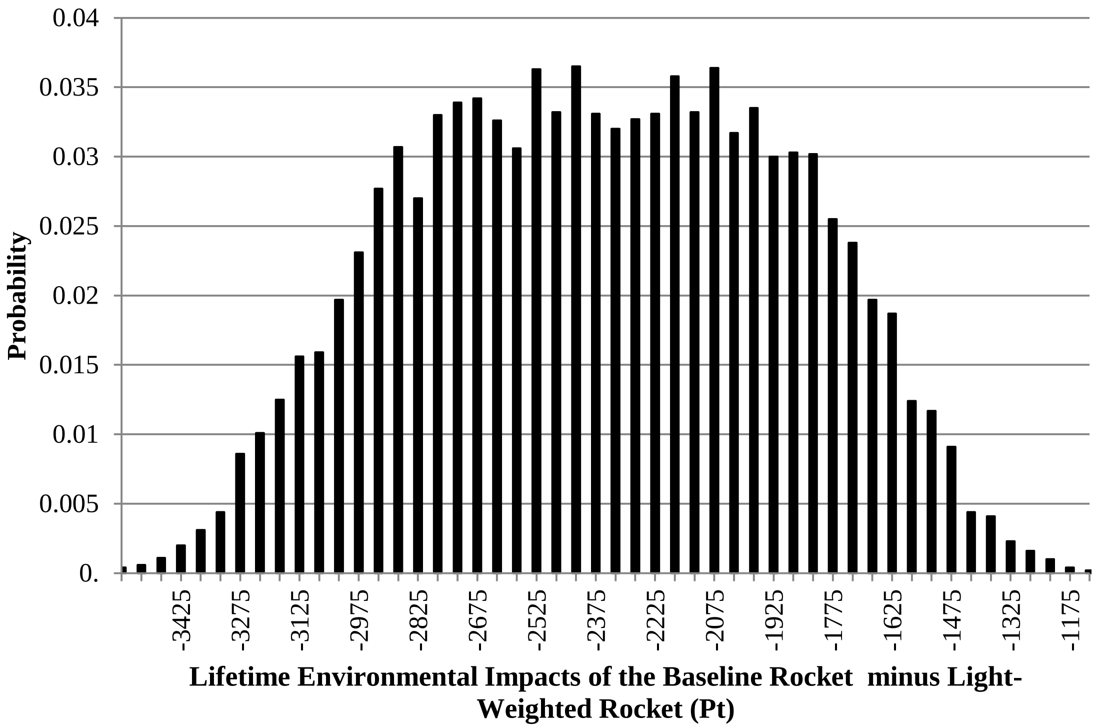


Figure 53: Probability density function showing the results from the low uncertainty analysis on the four stage, 1,500 kg to LEO, solid Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

As discussed in Chapter 9, the reason that the solid rocket experiences an increase in environmental impacts when light-weighted with CFRP's is that they are have high embodied impacts and are replacing metal (low alloy steel) in the motor casing that has much lower environmental impacts. The motor casing makes up a large proportion of the rocket's mass, meaning that this is a relatively large increase due to upstream impacts. Improvements that are the result of decreasing the propellant load of the rocket do not outweigh this large increase in upstream burdens.

Similar to what was seen with the LOX/LH2 rocket, there were tradeoffs amongst the impact categories. Light-weighting reduced environmental impacts in some categories, while increasing them in others. Solid propellants themselves have a much higher environmental impact than LOX/LH2 propellants, so it would normally be expected that structural materials wouldn't influence the results of the analysis as significantly. Therefore, such a tradeoff would not be expected. However, such a large portion of the rocket is being replaced by carbon fibers composites, and the metal they are replacing includes large amounts of relatively low impact steel. The solid propellant rocket's life cycle is still dominated by its propellants, but the greatest *change* in impacts occurs is associated with structural materials and not the propellants.

These tradeoffs have been discussed in Chapter 9 and can be clearly seen in Figure 54.

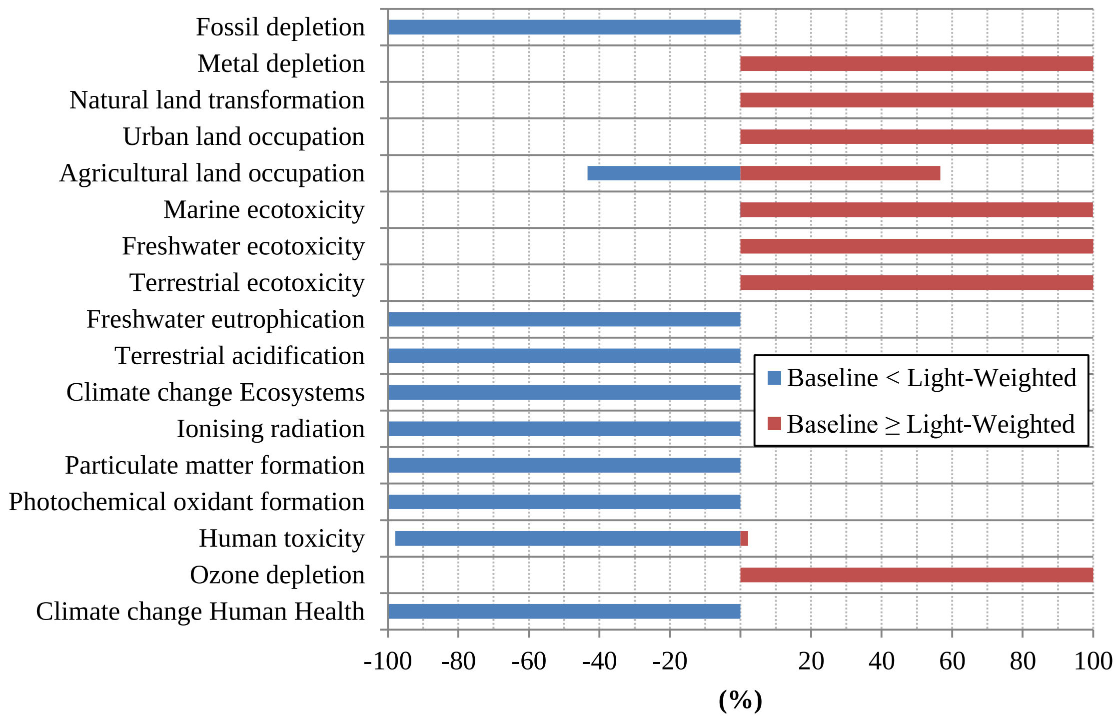


Figure 54: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the four stage, 1,500 kg to LEO, solid rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Conclusions about whether light-weighting with CFRP's was better for the environment by reducing impacts in the low uncertainty analysis are shown in Table 77. These conclusions are based on the ReCiPe 2008 Egalitarian Endpoint single score indicator. Probability distribution functions and category comparison plots for seven example rocket configuration pairs can be found in Appendix E.

Table 77: Conclusions about the environmental benefit of light-weighting when low uncertainty was assumed

Propellants	Stages	Confidently Better	Likely Better	Split	Likely Worse	Confidently Worse
LOX/LH2	2	**X**				
	3	**X**				
LOX/RP1	2	**X**				
	3	**X**				
N2O4/UDMH	2	**X**				
	3	**X**				
Solid	4					**X**

10.3 Moderate Uncertainty (±25%)

It was found that there was some interesting behavior with the LOX/LH2 rockets when an uncertainty of ±25% was included.

Though the results were very similar to the low uncertainty analysis, it was found that at one extreme that light-weighting could potentially be worse for the environment according to the single score indicator. This because the environmental impacts of consuming LOX/LH2 propellants are so small that a rocket using these propellants has its life cycle impacts most heavily influenced by changes in the structural material. Any reductions in propellant loads due to light-weighting do not change lifetime environmental impacts very much since these propellants had such a small impact in the first place. Changes in structural materials are relatively more pronounced. At this extreme, it was assumed that impacts of the baseline rocket were overestimated while impacts of the light-weighted rocket were underestimated. The probability of this occurring was quite small, but there were a non-negligible number of runs that resulted in light-weighting being worse. Nevertheless, it was found that it is very likely light-weighting is indeed better.

The results for the LOX/RP1 rockets and N2O4/UDMH rockets were still found to be always better, though by a smaller margin at one extreme.

It was originally concluded that light-weighting a solid propellant rocket would always be worse, and this was confirmed when low uncertainty was assumed. However, at the moderate level of uncertainty, there were cases where it was found that light-weighting was better for the environment. Though the probability of this occurring was small, it was still non-negligible.

The tradeoffs amongst each individual category in the moderate uncertainty analysis were quite similar as to what they were in the low uncertainty.

Conclusions about whether light-weighting with CFRP's was better for the environment by reducing impacts in the moderate uncertainty analysis are shown in Table 78. These conclusions are based on the single score indicator.

Table 78: Conclusions about the environmental benefit of light-weighting when low uncertainty was assumed

Propellants	Stages	Confidently Better	Likely Better	Split	Likely Worse	Confidently Worse
LOX/LH2	2		X			
	3		X			
LOX/RP1	2	X				
	3	X				
N2O4/UDMH	2	X				
	3	X				
Solid	4				X	

10.4 High Uncertainty (±50%)

As was the case in the moderate uncertainty analysis, it was found that the LOX/LH2 rockets could likely benefit from light-weighting, but there was a respectable probability that light-weighting could actually increase environmental impacts. It was found that the LOX/RP1 and the N2O4/UDMH rockets still always benefited from light-weighting.

Similar to the results in the moderate uncertainty analysis, solid propellant rockets were found to still be very likely to increase impacts when light-weighted, but there is some chance that they can reduce them.

The tradeoffs amongst each individual category in the high uncertainty analysis were similar as to what they were in both the low and moderate uncertainty analyses. However, there were some increased tradeoffs in impacts according to individual categories in the case of the LOX/RP1 rocket. These tradeoffs were relatively small, though non-negligible.

Conclusions about whether light-weighting with CFRP's was better for the environment by reducing impacts in the moderate uncertainty analysis are shown in Table 78. These conclusions are based on the single score indicator.

Table 79: Conclusions about the environmental benefit of light-weighting when low uncertainty was assumed

Propellants	Stages	Confidently Better	Likely Better	Split	Likely Worse	Confidently Worse
LOX/LH2	2			X		
	3			X		
LOX/RP1	2	X				
	3	X				
N2O4/UDMH	2	X				
	3	X				
Solid	4				X	

10.5 Discussion of Tradeoffs Amongst Impact Categories

10.5.1 Tradeoffs According to Propellants

The LOX/LH2 rocket saw significant tradeoffs between certain categories, even though light-weighting was found to generally be better for the environment. While being burned, LOX/LH2 produces almost no environmental burdens when compared to the other propellants. This pushes the emphasis more on the structure of the rocket. Carbon fiber composites and metals have different upstream burdens, so it was not expected that impacts would be the same across all categories so this result is not surprising.

10.5.2 Tradeoffs According to Number of Stages

It is expected from literature (Humble, Henry et al. 1995) that increasing the number of stages on a rocket increases the total inert mass fraction. This means that the mass fraction of the rocket that is propellants decreases, causing the environmental impacts associated with the structure to become relatively larger. This means that the differences between carbon fiber composites and metals become more pronounced, having a greater influence over impacts.

Per 1 kg to LEO, increasing the number of stages has the added benefit that empty or spent components of the rocket can be shed more frequently, meaning that the rocket doesn't have to lift these spent structure for as long a period of time. Increasing the number of stages *increases* the mass fraction of the rocket that is inert, but *decreases* the overall mass of the rocket. This means that the *relative* impacts of the structure of the rocket are increased, but the *absolute* impacts decrease.

10.5.3 Tradeoffs According to Lift Capacity

No discernible change in impacts, either with the single score indicator or in each individual impact category, was identified as being the result of different payload mass.

10.6 Chapter Summary

This chapter discussed the results of an uncertainty analysis performed on the life cycle impacts of rockets. Three different levels of uncertainty were considered: low, moderate, and high.

It was shown in Section 4.7 (beginning on page 93) that there are some difference between the rockets sized by the PRSM and real world rockets. It was also discussed that the data used in the analysis may not be perfectly representative of the various materials and processes used and consumed in a rocket's life cycle. The purpose of the uncertainty analysis is to account for potential errors in both the PRSM and the life cycle model in SimaPro. The results from the uncertainty analysis help ensure that the conclusions being drawn about the benefits of light-weighting with CFRP's are made with confidence and the initial analysis didn't happen to pick a particular configuration of rocket that is not representative of broader behavior.

It was concluded in Chapter 9 that light-weighting with CFRP's decreases lifetime environmental impacts for each of the liquid propellant rockets, while increasing environmental impacts for the solid propellant rockets. Out of the 10,000 simulations run during the Monte Carlo uncertainty analysis for seven example rockets, the percentage of runs that supported this conclusion are shown in Table 80.

Table 80: Percentage of times that the conclusion on whether light-weighting increased or decreased lifetime environmental impacts was upheld during each uncertainty analysis for different rocket configurations

Propellants	Stages	Conclusion (Chapter 9)	Low Uncertainty (±10%)	Moderate Uncertainty (±25%)	High Uncertainty (±50%)
			Times Conclusions Upheld (%)	Times Conclusions Upheld (%)	Times Conclusions Upheld (%)
LOX/LH2	2	Decrease	100.0%	97.9%	80.0%
	3	Decrease	100.0%	84.9%	68.4%
LOX/RP1	2	Decrease	100.0%	100.0%	100.0%
	3	Decrease	100.0%	100.0%	99.8%
N2O4/UDMH	2	Decrease	100.0%	100.0%	100.0%
	3	Decrease	100.0%	100.0%	100.0%
Solid	4	Increase	100.0%	98.8%	81.0%

If the percentage of runs supporting the conclusion is better than 95%, then it can be assumed with high confidence that light-weighting is an improvement. If the conclusion is supported at least 90% of the time, then the conclusion is assumed with a moderate level of confidence. A likelihood below 90% indicates that the conclusion is supported with a low level of confidence, and the results are considered inconclusive if the conclusion is supported 75% of the time or fewer.

Probability density functions and likelihood of tradeoffs according to categories for all rocket configurations considered, for each level of uncertainty are found in Appendix E.

11 Additional Scenarios and Discussion

11.1 Overview of Chapter Contents

The main analysis described in the previous chapters makes some assumptions to simplify the system. This chapter looks at the influence of slightly modifying those assumptions has on the outcomes detailed in Chapters 9 and 10. The purpose of this is to show that changing certain assumptions does not change the final conclusions drawn.

This chapter begins by analyzing some alternate scenarios. First, it was assumed that light-weighting reduced the rocket's mass by different amounts. Next, the analysis from Chapter 9 is repeated for certain rockets using a different impact assessment methodology to make sure that the results from Chapter 9 are not unique to the particular impact assessment method used.

This chapter goes on to discuss the influence including transportation would have had on the results of the impact assessment before going into some analysis to put a rocket's impacts into perspective by comparing it to an airplane's life cycle. Finally, military rockets and the global impact of rockets are discussed.

11.2 Alternate Scenarios

11.2.1 Light-Weighting Scenario with Different Light-Weighting Amounts

The analysis in the previous chapters has assumed that light-weighting can reduce the mass of a particular component by 25%. Two additional scenarios are assessed here. The first is where light-weighting only reduces the mass of a component by 10%, and the other where light-weighting reduces the mass of the component by 50%. The results, compared to the baseline and the 25% light-weighted rockets, are shown in Figure 55.

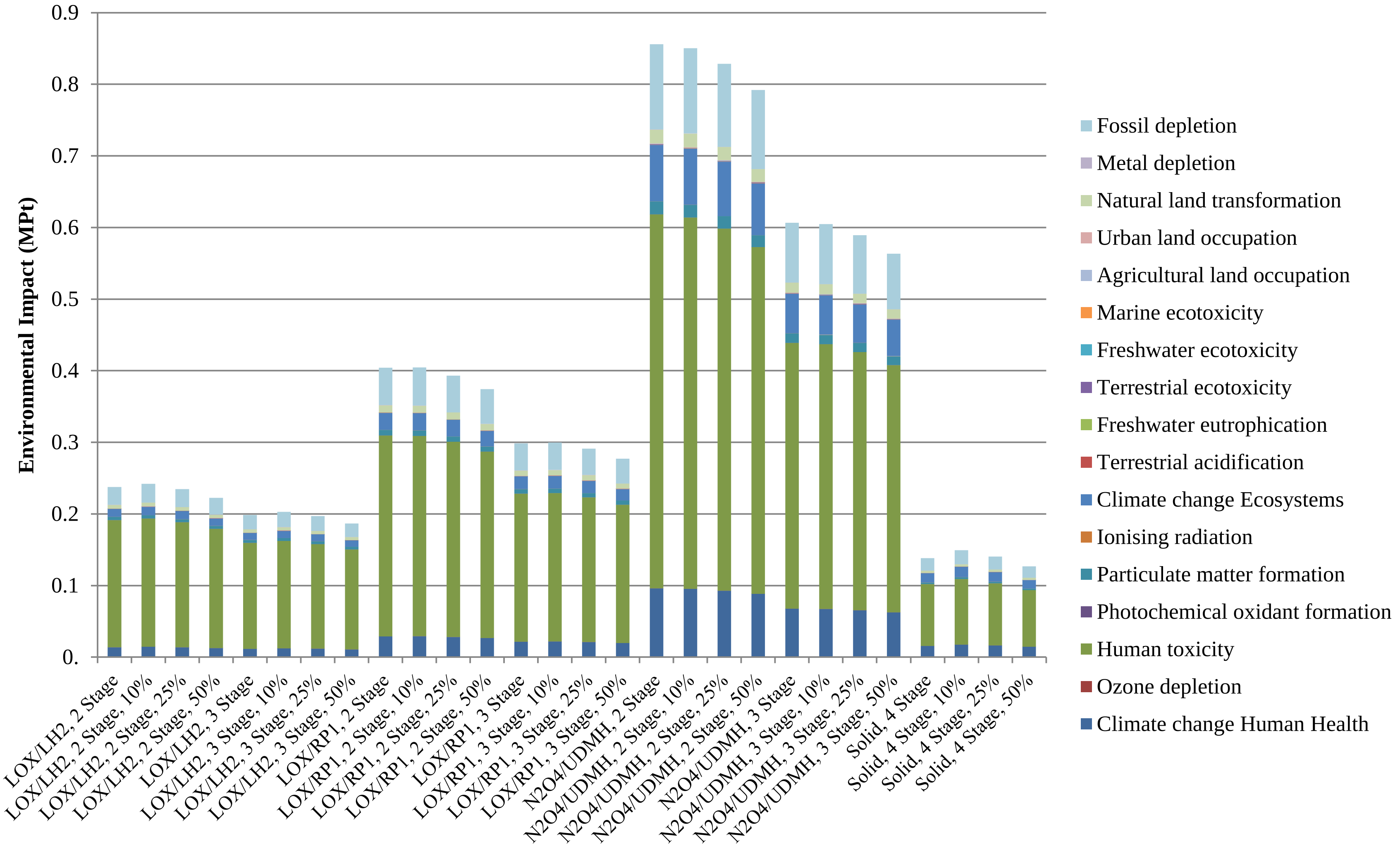


Figure 55: Environmental impacts of launching 1 kg to LEO assuming different light-weighting scenarios, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Table 81: Contributions by impact categories while comparing environmental impacts of launching 1 kg to LEO assuming different light-weighting scenarios, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 1)

Configuration	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification
LOX/LH2, 2 Stage	1.36E-02	9.20E-07	1.78E-01	6.32E-07	4.40E-03	2.34E-05	1.11E-02	1.00E-04
LOX/LH2, 2 Stage, 10%	1.44E-02	9.21E-07	1.79E-01	6.59E-07	4.40E-03	2.79E-05	1.18E-02	1.00E-04
LOX/LH2, 2 Stage, 25%	1.38E-02	8.89E-07	1.75E-01	6.34E-07	4.30E-03	2.63E-05	1.13E-02	1.00E-04
LOX/LH2, 2 Stage, 50%	1.27E-02	8.37E-07	1.67E-01	5.91E-07	4.00E-03	2.37E-05	1.03E-02	1.00E-04
LOX/LH2, 3 Stage	1.16E-02	7.59E-07	1.48E-01	5.55E-07	4.00E-03	1.95E-05	9.50E-03	1.00E-04
LOX/LH2, 3 Stage, 10%	1.24E-02	7.61E-07	1.50E-01	5.80E-07	4.00E-03	2.36E-05	1.01E-02	1.00E-04
LOX/LH2, 3 Stage, 25%	1.18E-02	7.35E-07	1.46E-01	5.58E-07	4.00E-03	2.22E-05	9.60E-03	1.00E-04
LOX/LH2, 3 Stage, 50%	1.08E-02	6.91E-07	1.40E-01	5.21E-07	3.70E-03	1.99E-05	8.80E-03	1.00E-04
LOX/RP1, 2 Stage	2.89E-02	3.58E-06	2.81E-01	1.13E-06	7.70E-03	4.06E-05	2.36E-02	2.00E-04
LOX/RP1, 2 Stage, 10%	2.93E-02	3.50E-06	2.80E-01	1.14E-06	7.70E-03	4.42E-05	2.39E-02	2.00E-04
LOX/RP1, 2 Stage, 25%	2.82E-02	3.41E-06	2.73E-01	1.10E-06	7.50E-03	4.22E-05	2.30E-02	2.00E-04
LOX/RP1, 2 Stage, 50%	2.65E-02	3.25E-06	2.61E-01	1.04E-06	7.10E-03	3.90E-05	2.17E-02	2.00E-04
LOX/RP1, 3 Stage	2.14E-02	2.55E-06	2.07E-01	8.70E-07	6.20E-03	2.99E-05	1.75E-02	2.00E-04
LOX/RP1, 3 Stage, 10%	2.18E-02	2.48E-06	2.07E-01	8.82E-07	6.20E-03	3.35E-05	1.78E-02	2.00E-04
LOX/RP1, 3 Stage, 25%	2.10E-02	2.41E-06	2.02E-01	8.53E-07	6.00E-03	3.19E-05	1.72E-02	2.00E-04
LOX/RP1, 3 Stage, 50%	1.97E-02	2.30E-06	1.93E-01	8.03E-07	5.70E-03	2.92E-05	1.60E-02	2.00E-04
N2O4/UDMH, 2 Stage	9.60E-02	1.55E-05	5.22E-01	6.12E-06	1.79E-02	2.00E-04	7.85E-02	5.00E-04
N2O4/UDMH, 2 Stage, 10%	9.55E-02	1.53E-05	5.18E-01	6.06E-06	1.78E-02	2.00E-04	7.80E-02	5.00E-04
N2O4/UDMH, 2 Stage, 25%	9.29E-02	1.49E-05	5.06E-01	5.90E-06	1.73E-02	2.00E-04	7.59E-02	5.00E-04
N2O4/UDMH, 2 Stage, 50%	8.86E-02	1.43E-05	4.84E-01	5.64E-06	1.65E-02	2.00E-04	7.24E-02	5.00E-04
N2O4/UDMH, 3 Stage	6.76E-02	1.08E-05	3.71E-01	4.31E-06	1.32E-02	1.00E-04	5.52E-02	4.00E-04
N2O4/UDMH, 3 Stage, 10%	6.74E-02	1.06E-05	3.70E-01	4.27E-06	1.30E-02	1.00E-04	5.51E-02	4.00E-04
N2O4/UDMH, 3 Stage, 25%	6.56E-02	1.04E-05	3.61E-01	4.16E-06	1.27E-02	1.00E-04	5.36E-02	4.00E-04
N2O4/UDMH, 3 Stage, 50%	6.24E-02	9.93E-06	3.46E-01	3.98E-06	1.22E-02	1.00E-04	5.10E-02	4.00E-04
Solid, 4 Stage	1.58E-02	1.44E-06	8.62E-02	5.10E-07	2.30E-03	3.67E-05	1.29E-02	5.85E-05
Solid, 4 Stage, 10%	1.75E-02	1.45E-06	9.17E-02	5.62E-07	2.50E-03	4.24E-05	1.43E-02	7.15E-05
Solid, 4 Stage, 25%	1.63E-02	1.38E-06	8.67E-02	5.25E-07	2.30E-03	3.94E-05	1.34E-02	6.59E-05
Solid, 4 Stage, 50%	1.46E-02	1.27E-06	7.90E-02	4.69E-07	2.00E-03	3.49E-05	1.19E-02	5.75E-05

Table 82: Contributions by impact categories while comparing environmental impacts of launching 1 kg to LEO assuming different light-weighting scenarios, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 2)

Configuration	Freshwater eutrophication	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
LOX/LH2, 2 Stage	2.97E-05	2.00E-04	4.76E-06	2.29E-05	1.00E-04	1.00E-04	5.20E-03	2.00E-04	2.48E-02
LOX/LH2, 2 Stage, 10%	3.12E-05	2.00E-04	4.79E-06	2.30E-05	1.00E-04	1.00E-04	5.10E-03	2.00E-04	2.62E-02
LOX/LH2, 2 Stage, 25%	3.01E-05	2.00E-04	4.65E-06	2.23E-05	1.00E-04	9.98E-05	5.00E-03	1.00E-04	2.52E-02
LOX/LH2, 2 Stage, 50%	2.83E-05	1.00E-04	4.42E-06	2.12E-05	9.98E-05	9.53E-05	4.70E-03	1.00E-04	2.35E-02
LOX/LH2, 3 Stage	2.47E-05	2.00E-04	4.18E-06	1.99E-05	9.55E-05	9.47E-05	4.70E-03	1.00E-04	2.00E-02
LOX/LH2, 3 Stage, 10%	2.61E-05	1.00E-04	4.21E-06	2.00E-05	1.00E-04	9.20E-05	4.60E-03	1.00E-04	2.13E-02
LOX/LH2, 3 Stage, 25%	2.52E-05	1.00E-04	4.09E-06	1.95E-05	9.66E-05	8.96E-05	4.50E-03	1.00E-04	2.04E-02
LOX/LH2, 3 Stage, 50%	2.37E-05	1.00E-04	3.89E-06	1.85E-05	9.05E-05	8.56E-05	4.20E-03	1.00E-04	1.90E-02
LOX/RP1, 2 Stage	4.71E-05	3.00E-04	7.63E-06	3.64E-05	2.00E-04	2.00E-04	9.80E-03	2.00E-04	5.23E-02
LOX/RP1, 2 Stage, 10%	4.80E-05	3.00E-04	7.58E-06	3.62E-05	2.00E-04	2.00E-04	9.60E-03	2.00E-04	5.30E-02
LOX/RP1, 2 Stage, 25%	4.65E-05	3.00E-04	7.38E-06	3.52E-05	2.00E-04	2.00E-04	9.30E-03	2.00E-04	5.13E-02
LOX/RP1, 2 Stage, 50%	4.41E-05	3.00E-04	7.03E-06	3.36E-05	1.00E-04	2.00E-04	8.90E-03	2.00E-04	4.85E-02
LOX/RP1, 3 Stage	3.48E-05	2.00E-04	5.90E-06	2.79E-05	1.00E-04	1.00E-04	7.60E-03	2.00E-04	3.79E-02
LOX/RP1, 3 Stage, 10%	3.59E-05	2.00E-04	5.88E-06	2.78E-05	1.00E-04	1.00E-04	7.40E-03	2.00E-04	3.81E-02
LOX/RP1, 3 Stage, 25%	3.47E-05	2.00E-04	5.72E-06	2.71E-05	1.00E-04	1.00E-04	7.20E-03	2.00E-04	3.69E-02
LOX/RP1, 3 Stage, 50%	3.28E-05	2.00E-04	5.45E-06	2.58E-05	1.00E-04	1.00E-04	6.90E-03	2.00E-04	3.48E-02
N2O4/UDMH, 2 Stage	1.00E-04	7.00E-04	1.43E-05	7.04E-05	6.00E-04	3.00E-04	1.92E-02	2.00E-04	1.19E-01
N2O4/UDMH, 2 Stage, 10%	1.00E-04	6.00E-04	1.42E-05	6.97E-05	6.00E-04	3.00E-04	1.89E-02	2.00E-04	1.19E-01
N2O4/UDMH, 2 Stage, 25%	1.00E-04	6.00E-04	1.38E-05	6.79E-05	6.00E-04	3.00E-04	1.84E-02	2.00E-04	1.16E-01
N2O4/UDMH, 2 Stage, 50%	1.00E-04	6.00E-04	1.32E-05	6.50E-05	5.00E-04	3.00E-04	1.76E-02	2.00E-04	1.10E-01
N2O4/UDMH, 3 Stage	9.12E-05	5.00E-04	1.04E-05	5.09E-05	4.00E-04	2.00E-04	1.40E-02	2.00E-04	8.35E-02
N2O4/UDMH, 3 Stage, 10%	9.15E-05	5.00E-04	1.03E-05	5.05E-05	4.00E-04	2.00E-04	1.38E-02	2.00E-04	8.38E-02
N2O4/UDMH, 3 Stage, 25%	8.91E-05	5.00E-04	1.01E-05	4.93E-05	4.00E-04	2.00E-04	1.34E-02	2.00E-04	8.14E-02
N2O4/UDMH, 3 Stage, 50%	8.50E-05	4.00E-04	9.63E-06	4.71E-05	4.00E-04	2.00E-04	1.28E-02	2.00E-04	7.76E-02
Solid, 4 Stage	2.29E-05	1.00E-04	2.48E-06	1.19E-05	1.00E-04	6.28E-05	3.40E-03	4.28E-05	1.71E-02
Solid, 4 Stage, 10%	2.51E-05	1.00E-04	2.59E-06	1.25E-05	1.00E-04	6.18E-05	3.40E-03	3.59E-05	1.95E-02
Solid, 4 Stage, 25%	2.35E-05	1.00E-04	2.45E-06	1.18E-05	1.00E-04	5.85E-05	3.20E-03	3.46E-05	1.80E-02
Solid, 4 Stage, 50%	2.12E-05	1.00E-04	2.22E-06	1.07E-05	1.00E-04	5.34E-05	2.90E-03	3.26E-05	1.60E-02

There is some interesting behavior when considering these different light-weighting scenarios.

Firstly, if only a 10% reduction in mass is assumed for both the two and three stage LOX/LH2 rockets, then the environmental impacts actually *increase* with light-weighting. This is because the propellant savings do not outweigh the increases in upstream burdens due to the use of carbon fibers. The CFRP material, as demonstrated in Figure 38 (page 172), has greater upstream environmental impacts than aluminum and low alloy steel. Even though the light-weighted component consumes a smaller mass of the material, the environmental impacts of the particular component can still increase. If the difference in mass between the baseline and the light-weighted component is too small, then not only are upstream impacts increased by a greater amount, but there are smaller mass savings in the overall inert mass of the rocket, and more importantly, in the total propellant load. What happens when it is assumed that light-weighting only reduces a components mass is that upstream burdens are increased while reducing downstream benefits by to such an extent that light-weighting actually increases lifetime environmental impacts.

Secondly, it is seen that both the LOX/RP1 and N2O4/UDMH always see an improvement with light-weighting, though the improvement with the LOX/RP1 rockets is almost negligible with a 10% mass reduction in certain components. Finally, it is seen that if the mass of the components assumed to be eligible for light-weighting on the solid rocket (specified in Chapter 4) decrease by 50%, then light-weighting actually *decreases* environmental impacts, which is contrary to the previous conclusions. With this amount of mass reduction in the solid propellant rockets, the propellant savings begin to outweigh the extra burdens due to the use of carbon fibers. This is the same effect that was described in the previous paragraph for the LOX/LH2 rockets, but the effect is going in the opposite direction.

11.2.2 Using a Different Impact Assessment Methodology

The impact assessment described in previous chapters used the ReCiPe 2008 impact assessment methodology. The same assessment was performed using the Eco-indicator 99 impact assessment methodology to cross validate the results. Eco-indicator 99 may be a bit outdated, but it was still a popular and widely used impact assessment method during its time. (PRE Consultants 2000) Results from the Eco-ndicator 99 impact assessment are shown in. These results match closely with the results obtained by using ReCiPe 2008.

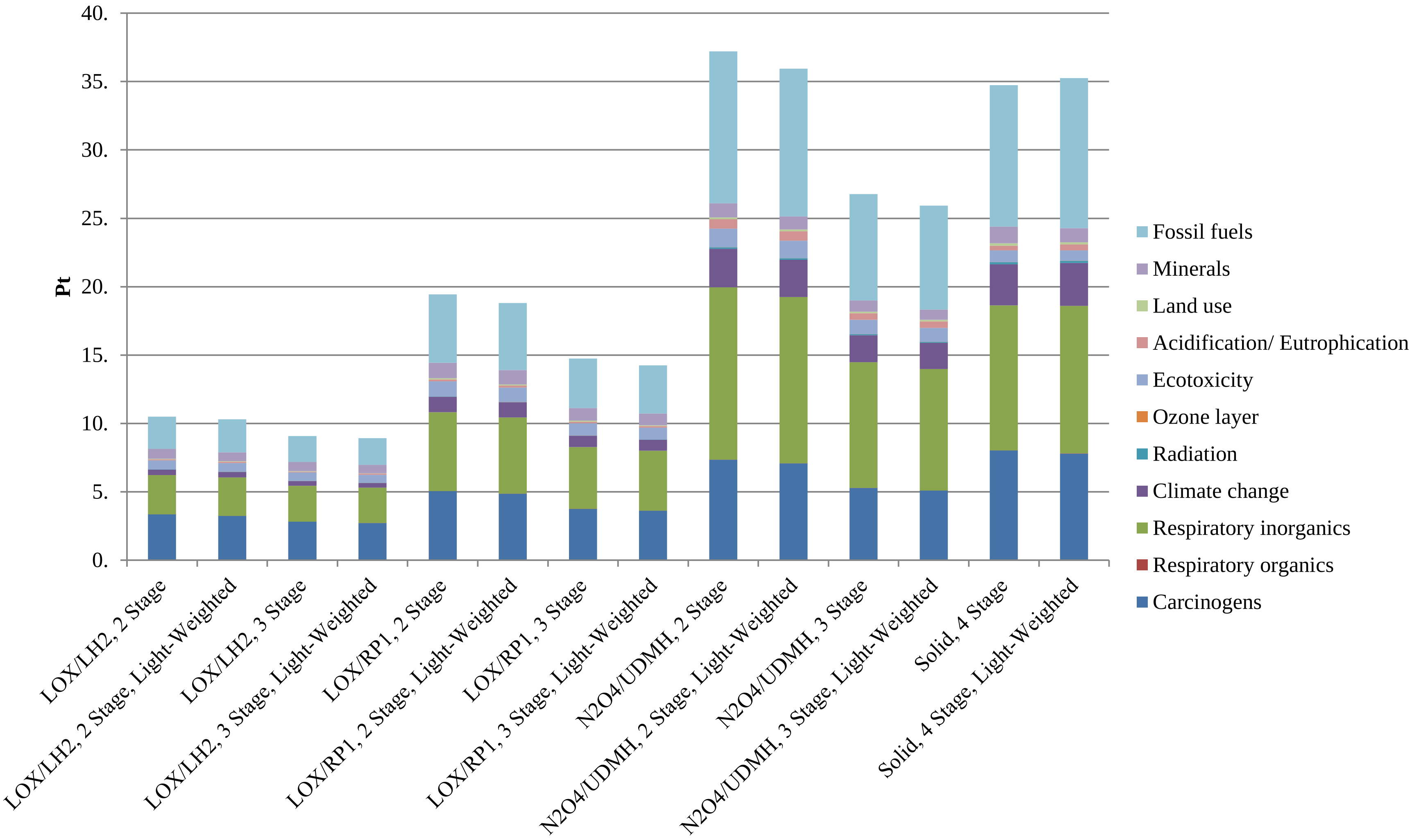


Figure 56: Life cycle impact assessment results for launching 1 kg to LEO, using Eco-indicator 99 methodology

Table 83: Contributions by impact category for the life cycle assessment results according to the Eco-indicator 99 methodology (Part 1)

Configuration	Carcinogens	Respiratory organics	Respiratory inorganics	Climate change	Radiation
LOX/LH2, 2 Stage	3.35E+00	1.70E-03	2.87E+00	3.93E-01	1.40E-02
LOX/LH2, 2 Stage, Light-Weighted	3.24E+00	1.60E-03	2.82E+00	4.01E-01	1.57E-02
LOX/LH2, 3 Stage	2.80E+00	1.40E-03	2.63E+00	3.33E-01	1.16E-02
LOX/LH2, 3 Stage, Light-Weighted	2.71E+00	1.40E-03	2.58E+00	3.42E-01	1.32E-02
LOX/RP1, 2 Stage	5.05E+00	3.10E-03	5.76E+00	1.14E+00	2.42E-02
LOX/RP1, 2 Stage, Light-Weighted	4.85E+00	3.00E-03	5.57E+00	1.11E+00	2.52E-02
LOX/RP1, 3 Stage	3.75E+00	2.30E-03	4.53E+00	8.23E-01	1.78E-02
LOX/RP1, 3 Stage, Light-Weighted	3.61E+00	2.20E-03	4.38E+00	8.07E-01	1.90E-02
N2O4/UDMH, 2 Stage	7.35E+00	5.50E-03	1.26E+01	2.80E+00	1.19E-01
N2O4/UDMH, 2 Stage, Light-Weighted	7.08E+00	5.30E-03	1.22E+01	2.72E+00	1.17E-01
N2O4/UDMH, 3 Stage	5.28E+00	3.90E-03	9.19E+00	1.97E+00	8.34E-02
N2O4/UDMH, 3 Stage, Light-Weighted	5.10E+00	3.80E-03	8.88E+00	1.92E+00	8.21E-02
Solid, 4 Stage	8.02E+00	8.00E-03	1.06E+01	3.01E+00	1.46E-01
Solid, 4 Stage, Light-Weighted	7.80E+00	8.00E-03	1.08E+01	3.13E+00	1.57E-01

Table 84: Contributions by impact category for the life cycle assessment results according to the Eco-indicator 99 methodology (Part 2)

Configuration	Ozone layer	Ecotoxicity	Acidification/ Eutrophication	Land use	Minerals	Fossil fuels
LOX/LH2, 2 Stage	2.00E-04	6.63E-01	7.85E-02	3.30E-02	7.22E-01	2.37E+00
LOX/LH2, 2 Stage, Light-Weighted	2.00E-04	6.36E-01	8.89E-02	3.13E-02	6.66E-01	2.40E+00
LOX/LH2, 3 Stage	1.00E-04	6.22E-01	7.07E-02	2.94E-02	6.70E-01	1.90E+00
LOX/LH2, 3 Stage, Light-Weighted	1.00E-04	5.97E-01	8.03E-02	2.78E-02	6.19E-01	1.94E+00
LOX/RP1, 2 Stage	7.00E-04	1.10E+00	1.41E-01	9.83E-02	1.12E+00	5.01E+00
LOX/RP1, 2 Stage, Light-Weighted	6.00E-04	1.05E+00	1.48E-01	9.37E-02	1.05E+00	4.91E+00
LOX/RP1, 3 Stage	5.00E-04	8.99E-01	1.11E-01	7.30E-02	9.15E-01	3.62E+00
LOX/RP1, 3 Stage, Light-Weighted	4.00E-04	8.62E-01	1.18E-01	6.91E-02	8.53E-01	3.52E+00
N2O4/UDMH, 2 Stage	3.30E-03	1.35E+00	6.87E-01	1.53E-01	1.03E+00	1.11E+01
N2O4/UDMH, 2 Stage, Light-Weighted	3.20E-03	1.29E+00	6.73E-01	1.46E-01	9.60E-01	1.08E+01
N2O4/UDMH, 3 Stage	2.30E-03	1.05E+00	4.87E-01	1.10E-01	8.16E-01	7.78E+00
N2O4/UDMH, 3 Stage, Light-Weighted	2.20E-03	1.01E+00	4.80E-01	1.05E-01	7.61E-01	7.59E+00
Solid, 4 Stage	2.00E-03	8.58E-01	3.51E-01	1.66E-01	1.23E+00	1.03E+01
Solid, 4 Stage, Light-Weighted	2.00E-03	7.64E-01	4.43E-01	1.58E-01	1.02E+00	1.10E+01

Several other impact assessment methodologies were also used to cross validate the results. TRACI 2.0, CML 2000, and BEES were used to run the assessments. These indicator sets use the midpoint method, so results are not tabulated in a single score. These confirmed a tradeoff in impact categories, as was expected by the analysis using ReCiPe. None of these alternate assessments suggested that the results obtained using ReCiPe were misleading.

The results from the TRACI 2.0 are found in Table 85 and Table 86, while the results according to CML 2000 Table 87 and Table 88, while the results according to BEES impact assessments are given in Table 89 and Table 90.

Table 85: Life cycle impact assessment results for the LOX/LH2 and LOX/RP1 rockets according to TRACI 2.0, normalized for 1 kg of payload to LEO, using the midpoint indicator

Impact category	Unit	LOX/LH2, 2 Stage, 10000 kg Payload	LOX/LH2, 2 Stage, 10000 kg Payload, LW	LOX/LH2, 3 Stage, 10000 kg Payload	LOX/LH2, 3 Stage, 10000 kg Payload LW	LOX/RP1, 2 Stage, 10000 kg Payload	LOX/RP1, 2 Stage, 10000 kg Payload, LW	LOX/RP1, 3 Stage, 10000 kg Payload	LOX/RP1, 3 Stage, 10000 kg Payload LW
Global warming	kg CO2 eq	4.15E+01	4.24E+01	3.52E+01	3.61E+01	1.21E+02	1.18E+02	8.72E+01	8.55E+01
Acidification	H+ moles eq	3.02E+01	3.05E+01	2.81E+01	2.84E+01	5.57E+01	5.47E+01	4.50E+01	4.44E+01
Carcinogenics	kg benzen eq	5.45E-01	5.23E-01	4.80E-01	4.61E-01	8.38E-01	8.03E-01	6.53E-01	6.26E-01
Non carcinogenics	kg toluen eq	5.72E+03	5.56E+03	4.89E+03	4.75E+03	8.72E+03	8.41E+03	6.60E+03	6.38E+03
Respiratory effects	kg PM2.5 eq	1.70E-01	1.65E-01	1.58E-01	1.53E-01	3.07E-01	2.95E-01	2.48E-01	2.39E-01
Eutrophication	kg N eq	3.60E-01	3.64E-01	2.98E-01	3.03E-01	6.16E-01	5.90E-01	4.37E-01	4.35E-01
Ozone depletion	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ecotoxicity	kg 2,4-D eq	3.83E+02	3.60E+02	3.33E+02	3.12E+02	5.85E+02	5.52E+02	4.51E+02	4.24E+02
Smog	g NOx eq	9.60E-02	9.90E-02	8.30E-02	8.60E-02	4.63E-01	4.50E-01	3.30E-01	3.21E-01

Table 86: Life cycle impact assessment results for the N2O4/UDMH and solid rockets according to TRACI 2.0, normalized for 1 kg of payload to LEO, using the midpoint indicator

Impact category	Unit	N2O4/UDMH, 2 Stage, 10000 kg Payload	N2O4/UDMH, 2 Stage, 10000 kg Payload LW	N2O4/UDMH, 3 Stage, 10000 kg Payload	N2O4/UDMH, 3 Stage, 10000 kg Payload LW	Solid, 4 Stage, 1500 kg Payload	Solid, 4 Stage, 1500 kg Payload LW
Global warming	kg CO2 eq	2.96E+02	2.87E+02	2.08E+02	2.02E+02	3.17E+02	3.30E+02
Acidification	H+ moles eq	1.27E+02	1.23E+02	9.37E+01	9.13E+01	4.99E+02	4.77E+02
Carcinogenics	kg benzen eq	1.34E+00	1.28E+00	9.85E-01	9.46E-01	2.05E+00	1.93E+00
Non carcinogenics	kg toluen eq	1.27E+04	1.22E+04	9.23E+03	8.93E+03	3.18E+04	2.99E+04
Respiratory effects	kg PM2.5 eq	5.39E-01	5.19E-01	4.04E-01	3.90E-01	5.86E-01	5.81E-01
Eutrophication	kg N eq	8.47E+00	8.15E+00	5.87E+00	5.66E+00	1.82E+00	1.88E+00
Ozone depletion	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ecotoxicity	kg 2,4-D eq	1.06E+03	1.01E+03	7.68E+02	7.31E+02	1.74E+03	1.68E+03
Smog	g NOx eq	1.48E+00	1.43E+00	1.04E+00	1.00E+00	7.10E-01	7.37E-01

Table 87: Life cycle impact assessment results for the LOX/LH2 and LOX/RP1 rockets according to CML 2001, normalized for 1 kg of payload to LEO, using the midpoint indicator

Impact category	Unit	LOX/LH2, 2 Stage, 10000 kg Payload	LOX/LH2, 2 Stage, 10000 kg Payload, LW	LOX/LH2, 3 Stage, 10000 kg Payload	LOX/LH2, 3 Stage, 10000 kg Payload LW	LOX/RP1, 2 Stage, 10000 kg Payload	LOX/RP1, 2 Stage, 10000 kg Payload, LW	LOX/RP1, 3 Stage, 10000 kg Payload	LOX/RP1, 3 Stage, 10000 kg Payload LW
Abiotic depletion	kg Sb eq	4.50E-01	4.60E-01	3.64E-01	3.75E-01	8.98E-01	8.84E-01	6.53E-01	6.39E-01
Acidification	kg SO2 eq	6.69E-01	6.68E-01	6.26E-01	6.25E-01	1.24E+00	1.21E+00	1.01E+00	9.85E-01
Eutrophication	kg PO4--- eq	1.62E-01	1.67E-01	1.34E-01	1.39E-01	2.71E-01	2.63E-01	1.93E-01	1.95E-01
Global warming 20a	kg CO2 eq	4.70E+01	4.84E+01	3.95E+01	4.09E+01	1.25E+02	1.23E+02	9.07E+01	8.92E+01
Global warming 100a	kg CO2 eq	4.15E+01	4.24E+01	3.51E+01	3.61E+01	1.21E+02	1.18E+02	8.72E+01	8.55E+01
Global warming 500a	kg CO2 eq	3.92E+01	3.99E+01	3.33E+01	3.41E+01	1.18E+02	1.15E+02	8.57E+01	8.38E+01
Upper limit of net global warming	kg CO2 eq	4.19E+01	4.29E+01	3.55E+01	3.65E+01	1.53E+02	1.49E+02	1.09E+02	1.07E+02
Lower limit of net global warming	kg CO2 eq	4.16E+01	4.27E+01	3.52E+01	3.63E+01	1.08E+02	1.06E+02	7.88E+01	7.75E+01
Ozone layer depletion 5a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 10a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 15a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 20a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 25a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 30a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 40a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion steady state	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human toxicity 20a	kg 1,4-DB eq	1.68E+02	1.48E+02	1.60E+02	1.42E+02	2.66E+02	2.43E+02	2.23E+02	2.02E+02
Human toxicity 100a	kg 1,4-DB eq	1.68E+02	1.48E+02	1.60E+02	1.42E+02	2.66E+02	2.43E+02	2.23E+02	2.02E+02
Human toxicity 500a	kg 1,4-DB eq	1.68E+02	1.48E+02	1.60E+02	1.42E+02	2.67E+02	2.43E+02	2.24E+02	2.02E+02
Human toxicity infinite	kg 1,4-DB eq	2.06E+02	1.85E+02	1.92E+02	1.73E+02	3.27E+02	3.01E+02	2.69E+02	2.46E+02
Freshwater aquatic ecotox. 20a	kg 1,4-DB eq	4.77E+01	4.57E+01	4.20E+01	4.03E+01	7.48E+01	7.16E+01	5.82E+01	5.57E+01
Freshwater aquatic ecotox. 100a	kg 1,4-DB eq	5.02E+01	4.82E+01	4.43E+01	4.25E+01	7.88E+01	7.54E+01	6.13E+01	5.87E+01
Freshwater aquatic ecotox. 500a	kg 1,4-DB eq	5.04E+01	4.83E+01	4.44E+01	4.26E+01	7.91E+01	7.57E+01	6.16E+01	5.89E+01
Fresh water aquatic ecotox. infinite	kg 1,4-DB eq	5.09E+01	4.88E+01	4.49E+01	4.31E+01	8.00E+01	7.65E+01	6.23E+01	5.96E+01
Marine aquatic ecotox. 20a	kg 1,4-DB eq	2.79E+01	2.67E+01	2.47E+01	2.37E+01	4.57E+01	4.36E+01	3.55E+01	3.39E+01
Marine aquatic ecotox. 100a	kg 1,4-DB eq	1.85E+02	1.77E+02	1.64E+02	1.57E+02	2.97E+02	2.84E+02	2.31E+02	2.21E+02

Impact category	Unit	LOX/LH2, 2 Stage, 10000 kg Payload	LOX/LH2, 2 Stage, 10000 kg Payload, LW	LOX/LH2, 3 Stage, 10000 kg Payload	LOX/LH2, 3 Stage, 10000 kg Payload LW	LOX/RP1, 2 Stage, 10000 kg Payload	LOX/RP1, 2 Stage, 10000 kg Payload, LW	LOX/RP1, 3 Stage, 10000 kg Payload	LOX/RP1, 3 Stage, 10000 kg Payload LW
Marine aquatic ecotox. 500a	kg 1,4-DB eq	9.87E+02	9.47E+02	8.73E+02	8.39E+02	1.58E+03	1.51E+03	1.23E+03	1.18E+03
Marine aquatic ecotoxicity infinite	kg 1,4-DB eq	9.97E+04	9.72E+04	8.53E+04	8.34E+04	1.60E+05	1.55E+05	1.21E+05	1.17E+05
Terrestrial ecotoxicity 20a	kg 1,4-DB eq	9.00E-03	8.00E-03	8.00E-03	8.00E-03	1.50E-02	1.50E-02	1.30E-02	1.20E-02
Terrestrial ecotoxicity 100a	kg 1,4-DB eq	3.70E-02	3.60E-02	3.50E-02	3.40E-02	6.60E-02	6.30E-02	5.40E-02	5.20E-02
Terrestrial ecotoxicity 500a	kg 1,4-DB eq	1.20E-01	1.16E-01	1.12E-01	1.09E-01	2.09E-01	2.01E-01	1.69E-01	1.64E-01
Terrestrial ecotoxicity infinite	kg 1,4-DB eq	4.90E-01	4.45E-01	4.54E-01	4.14E-01	8.00E-01	7.39E-01	6.50E-01	5.99E-01
Marine sediment ecotox. 20a	kg 1,4-DB eq	4.60E+01	4.37E+01	4.10E+01	3.90E+01	7.52E+01	7.15E+01	5.89E+01	5.59E+01
Marine sediment ecotox. 100a	kg 1,4-DB eq	1.93E+02	1.84E+02	1.72E+02	1.64E+02	3.10E+02	2.96E+02	2.43E+02	2.32E+02
Marine sediment ecotox. 500a	kg 1,4-DB eq	8.52E+02	8.15E+02	7.59E+02	7.27E+02	1.37E+03	1.31E+03	1.07E+03	1.02E+03
Marine sediment ecotox. infinite	kg 1,4-DB eq	5.93E+04	5.74E+04	5.14E+04	4.99E+04	9.67E+04	9.30E+04	7.40E+04	7.12E+04
Freshwater sediment ecotox. 20a	kg 1,4-DB eq	9.99E+01	9.54E+01	8.86E+01	8.48E+01	1.57E+02	1.50E+02	1.23E+02	1.17E+02
Freshwater sediment ecotox. 100a	kg 1,4-DB eq	1.06E+02	1.02E+02	9.45E+01	9.04E+01	1.67E+02	1.60E+02	1.31E+02	1.25E+02
Freshwater sediment ecotox. 500a	kg 1,4-DB eq	1.07E+02	1.02E+02	9.48E+01	9.07E+01	1.68E+02	1.60E+02	1.32E+02	1.26E+02
Freshwater sediment ecotox. infinite	kg 1,4-DB eq	1.08E+02	1.03E+02	9.55E+01	9.13E+01	1.69E+02	1.62E+02	1.33E+02	1.27E+02
Average European (kg NOx eq)	kg NOx eq	1.28E-01	1.72E-01	1.11E-01	1.51E-01	2.21E-01	2.58E-01	1.68E-01	2.04E-01
Average European (kg SO2-Eq)	kg SO2 eq	6.66E-01	6.65E-01	6.23E-01	6.22E-01	1.23E+00	1.21E+00	1.00E+00	9.81E-01
Land competition	m2a	9.93E-01	9.79E-01	8.95E-01	8.84E-01	1.59E+00	1.54E+00	1.26E+00	1.23E+00
Ionising radiation	DALYs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Photochemical oxidation	kg C2H4	3.00E-02	2.90E-02	2.80E-02	2.70E-02	6.52E-01	6.25E-01	4.53E-01	4.35E-01
Photochemical oxidation (low NOx)	kg C2H4 eq	7.00E-03	6.00E-03	6.00E-03	5.00E-03	1.10E-02	1.00E-02	9.00E-03	8.00E-03
Malodours air	m3 air	5.17E+05	5.36E+05	4.17E+05	4.37E+05	6.31E+05	6.37E+05	4.88E+05	4.78E+05
Equal benefit incremental reactivity	kg formed O3	8.00E-03	7.00E-03	7.00E-03	6.00E-03	1.30E-02	1.20E-02	1.00E-02	9.00E-03
Max. incremental reactivity	kg formed O3	4.00E-03	3.00E-03	3.00E-03	3.00E-03	6.00E-03	6.00E-03	5.00E-03	5.00E-03
Max. ozone incremental reactivity	kg formed O3	6.00E-03	5.00E-03	6.00E-03	5.00E-03	1.10E-02	1.00E-02	8.00E-03	7.00E-03

Table 88: Life cycle impact assessment results for the N2O4/UDMH and solid rockets according to CML 2001, normalized for 1 kg of payload to LEO, using the midpoint indicator

Impact category	Unit	N2O4/UDMH, 2 Stage, 10000 kg Payload	N2O4/UDMH, 2 Stage, 10000 kg Payload LW	N2O4/UDMH, 3 Stage, 10000 kg Payload	N2O4/UDMH, 3 Stage, 10000 kg Payload LW	Solid, 4 Stage, 1500 kg Payload	Solid, 4 Stage, 1500 kg Payload LW
Abiotic depletion	kg Sb eq	2.25E+00	2.18E+00	1.57E+00	1.54E+00	2.24E+00	2.37E+00
Acidification	kg SO2 eq	2.36E+00	2.29E+00	1.76E+00	1.72E+00	9.93E+00	9.46E+00
Eutrophication	kg PO4--- eq	3.74E+00	3.60E+00	2.59E+00	2.50E+00	8.28E-01	8.79E-01
Global warming 20a	kg CO2 eq	3.15E+02	3.06E+02	2.21E+02	2.16E+02	3.35E+02	3.50E+02
Global warming 100a	kg CO2 eq	2.96E+02	2.87E+02	2.08E+02	2.02E+02	3.17E+02	3.30E+02
Global warming 500a	kg CO2 eq	2.87E+02	2.78E+02	2.02E+02	1.96E+02	3.09E+02	3.21E+02
Upper limit of net global warming	kg CO2 eq	3.09E+02	3.00E+02	2.17E+02	2.11E+02	3.27E+02	3.40E+02
Lower limit of net global warming	kg CO2 eq	3.00E+02	2.90E+02	2.11E+02	2.05E+02	3.13E+02	3.27E+02
Ozone layer depletion 5a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 10a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 15a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 20a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 25a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 30a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion 40a	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ozone layer depletion steady state	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human toxicity 20a	kg 1,4-DB eq	2.64E+02	2.41E+02	2.15E+02	1.95E+02	4.84E+02	4.27E+02
Human toxicity 100a	kg 1,4-DB eq	2.64E+02	2.41E+02	2.15E+02	1.95E+02	4.85E+02	4.28E+02
Human toxicity 500a	kg 1,4-DB eq	2.66E+02	2.42E+02	2.16E+02	1.96E+02	4.86E+02	4.29E+02
Human toxicity infinite	kg 1,4-DB eq	3.73E+02	3.46E+02	2.93E+02	2.70E+02	6.04E+02	5.45E+02
Freshwater aquatic ecotox. 20a	kg 1,4-DB eq	1.36E+02	1.30E+02	9.91E+01	9.53E+01	1.81E+02	1.76E+02
Freshwater aquatic ecotox. 100a	kg 1,4-DB eq	1.43E+02	1.37E+02	1.04E+02	1.00E+02	1.90E+02	1.84E+02
Freshwater aquatic ecotox. 500a	kg 1,4-DB eq	1.44E+02	1.38E+02	1.05E+02	1.01E+02	1.90E+02	1.85E+02
Fresh water aquatic ecotox. infinite	kg 1,4-DB eq	1.46E+02	1.40E+02	1.07E+02	1.03E+02	1.92E+02	1.87E+02
Marine aquatic ecotox. 20a	kg 1,4-DB eq	8.85E+01	8.49E+01	6.44E+01	6.18E+01	1.07E+02	1.04E+02
Marine aquatic ecotox. 100a	kg 1,4-DB eq	5.67E+02	5.44E+02	4.13E+02	3.97E+02	6.91E+02	6.71E+02
Marine aquatic ecotox. 500a	kg 1,4-DB eq	3.01E+03	2.89E+03	2.19E+03	2.11E+03	3.65E+03	3.54E+03

Impact category	Unit	N2O4/UDMH, 2 Stage, 10000 kg Payload	N2O4/UDMH, 2 Stage, 10000 kg Payload LW	N2O4/UDMH, 3 Stage, 10000 kg Payload	N2O4/UDMH, 3 Stage, 10000 kg Payload LW	Solid, 4 Stage, 1500 kg Payload	Solid, 4 Stage, 1500 kg Payload LW
Marine aquatic ecotoxicity infinite	kg 1,4-DB eq	3.18E+05	3.07E+05	2.28E+05	2.21E+05	3.60E+05	3.59E+05
Terrestrial ecotoxicity 20a	kg 1,4-DB eq	4.50E-02	4.30E-02	3.30E-02	3.20E-02	2.20E-02	2.00E-02
Terrestrial ecotoxicity 100a	kg 1,4-DB eq	2.07E-01	1.99E-01	1.50E-01	1.45E-01	9.60E-02	8.90E-02
Terrestrial ecotoxicity 500a	kg 1,4-DB eq	7.86E-01	7.56E-01	5.65E-01	5.45E-01	3.84E-01	3.57E-01
Terrestrial ecotoxicity infinite	kg 1,4-DB eq	2.58E+00	2.45E+00	1.86E+00	1.77E+00	2.33E+00	2.14E+00
Marine sediment ecotox. 20a	kg 1,4-DB eq	1.43E+02	1.37E+02	1.05E+02	1.00E+02	1.85E+02	1.79E+02
Marine sediment ecotox. 100a	kg 1,4-DB eq	5.87E+02	5.63E+02	4.29E+02	4.12E+02	7.40E+02	7.15E+02
Marine sediment ecotox. 500a	kg 1,4-DB eq	2.60E+03	2.50E+03	1.90E+03	1.83E+03	3.23E+03	3.13E+03
Marine sediment ecotox. infinite	kg 1,4-DB eq	1.93E+05	1.86E+05	1.39E+05	1.34E+05	2.24E+05	2.21E+05
Freshwater sediment ecotox. 20a	kg 1,4-DB eq	2.82E+02	2.71E+02	2.07E+02	1.98E+02	3.89E+02	3.76E+02
Freshwater sediment ecotox. 100a	kg 1,4-DB eq	3.00E+02	2.88E+02	2.20E+02	2.11E+02	4.13E+02	3.99E+02
Freshwater sediment ecotox. 500a	kg 1,4-DB eq	3.02E+02	2.89E+02	2.21E+02	2.12E+02	4.13E+02	4.00E+02
Freshwater sediment ecotox. infinite	kg 1,4-DB eq	3.07E+02	2.94E+02	2.25E+02	2.16E+02	4.17E+02	4.03E+02
Average European (kg NOx eq)	kg NOx eq	1.80E+00	1.78E+00	1.26E+00	1.25E+00	7.59E-01	1.11E+00
Average European (kg SO2-Eq)	kg SO2 eq	2.34E+00	2.27E+00	1.75E+00	1.71E+00	1.98E+00	2.11E+00
Land competition	m2a	4.62E+00	4.47E+00	3.34E+00	3.23E+00	6.05E+00	5.95E+00
Ionising radiation	DALYs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Photochemical oxidation	kg C2H4	2.06E-01	1.98E-01	1.48E-01	1.42E-01	2.66E-01	2.52E-01
Photochemical oxidation (low NOx)	kg C2H4 eq	2.70E-02	2.50E-02	1.90E-02	1.80E-02	4.70E-02	4.20E-02
Malodours air	m3 air	3.45E+06	3.35E+06	2.41E+06	2.35E+06	2.04E+06	2.18E+06
Equal benefit incremental reactivity	kg formed O3	3.20E-02	3.00E-02	2.30E-02	2.10E-02	4.80E-02	4.40E-02
Max. incremental reactivity	kg formed O3	1.80E-02	1.70E-02	1.30E-02	1.20E-02	2.30E-02	2.10E-02
Max. ozone incremental reactivity	kg formed O3	2.70E-02	2.50E-02	1.90E-02	1.80E-02	3.90E-02	3.50E-02

Table 89: Life cycle impact assessment results for the LOX/LH2 and LOX/RP1 rockets according to BEES, normalized for 1 kg of payload to LEO, using the midpoint indicator

Impact category	Unit	LOX/LH2, 2 Stage, 10000 kg Payload	LOX/LH2, 2 Stage, 10000 kg Payload, LW	LOX/LH2, 3 Stage, 10000 kg Payload	LOX/LH2, 3 Stage, 10000 kg Payload LW	LOX/RP1, 2 Stage, 10000 kg Payload	LOX/RP1, 2 Stage, 10000 kg Payload, LW	LOX/RP1, 3 Stage, 10000 kg Payload	LOX/RP1, 3 Stage, 10000 kg Payload LW
Global warming	g CO2 eq	4.10E+04	4.20E+04	3.47E+04	3.58E+04	8.51E+04	8.38E+04	6.29E+04	6.23E+04
Acidification	H+ moles eq	3.02E+04	3.26E+04	2.81E+04	3.03E+04	5.57E+04	5.68E+04	4.50E+04	4.63E+04
HH cancer	g C6H6 eq	8.80E+02	8.46E+02	7.72E+02	7.43E+02	1.42E+03	1.36E+03	1.10E+03	1.05E+03
HH noncancer	g C7H7 eq	9.59E+05	1.68E+06	8.46E+05	1.50E+06	1.53E+06	2.20E+06	1.19E+06	1.81E+06
HH criteria air pollutants	microDALYs	1.25E+01	1.20E+01	1.16E+01	1.11E+01	2.19E+01	2.10E+01	1.77E+01	1.69E+01
Eutrophication	g N eq	1.04E+03	1.05E+03	8.60E+02	8.76E+02	1.69E+03	1.65E+03	1.23E+03	1.22E+03
Ecotoxicity	g 2,4-D eq	7.92E+02	7.79E+02	7.28E+02	7.16E+02	1.74E+03	1.68E+03	1.34E+03	1.30E+03
Smog	g NOx eq	1.19E+02	1.23E+02	1.03E+02	1.07E+02	5.76E+02	5.60E+02	4.10E+02	4.00E+02
Natural resource depletion	MJ surplus	1.09E+02	1.06E+02	8.60E+01	8.40E+01	2.22E+02	2.14E+02	1.60E+02	1.52E+02
Indoor air quality	kg TVOC eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Habitat alteration	T&E count	2.39E-12	2.31E-12	2.02E-12	1.96E-12	8.31E-12	7.96E-12	6.02E-12	5.70E-12
Water intake	liters	5.49E+05	4.71E+05	5.03E+05	4.32E+05	8.30E+05	7.40E+05	6.76E+05	5.95E+05
Ozone depletion	g CFC-11 eq	1.12E-03	9.98E-04	9.93E-04	8.82E-04	9.53E-03	8.95E-03	6.65E-03	6.28E-03

Table 90: Life cycle impact assessment results for the N2O4/UDMH and solid rockets according to BEES, normalized for 1 kg of payload to LEO, using the midpoint indicator

Impact category	Unit	N2O4/UDMH, 2 Stage, 10000 kg Payload	N2O4/UDMH, 2 Stage, 10000 kg Payload LW	N2O4/UDMH, 3 Stage, 10000 kg Payload	N2O4/UDMH, 3 Stage, 10000 kg Payload LW	Solid, 4 Stage, 1500 kg Payload	Solid, 4 Stage, 1500 kg Payload LW
Global warming	g CO2 eq	2.88E+05	2.79E+05	2.02E+05	1.97E+05	3.02E+05	3.17E+05
Acidification	H+ moles eq	1.27E+05	1.26E+05	9.37E+04	9.33E+04	4.99E+05	4.93E+05
HH cancer	g C6H6 eq	2.04E+03	1.96E+03	1.51E+03	1.45E+03	2.05E+03	1.95E+03
HH noncancer	g C7H7 eq	3.19E+06	3.79E+06	2.32E+06	2.90E+06	3.19E+06	8.72E+06
HH criteria air pollutants	microDALYs	3.77E+01	3.62E+01	2.82E+01	2.71E+01	4.61E+01	4.49E+01
Eutrophication	g N eq	1.32E+04	1.28E+04	9.20E+03	8.89E+03	5.28E+03	5.43E+03
Ecotoxicity	g 2,4-D eq	4.67E+03	4.51E+03	3.36E+03	3.24E+03	3.08E+03	2.82E+03
Smog	g NOx eq	1.85E+03	1.78E+03	1.29E+03	1.25E+03	8.80E+02	9.15E+02
Natural resource depletion	MJ surplus	4.78E+02	4.60E+02	3.34E+02	3.22E+02	3.71E+02	3.72E+02
Indoor air quality	kg TVOC eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Habitat alteration	T&E count	1.30E-11	1.25E-11	9.19E-12	8.85E-12	9.24E-12	9.21E-12
Water intake	liters	1.66E+06	1.54E+06	1.23E+06	1.13E+06	3.76E+06	3.59E+06
Ozone depletion	g CFC-11 eq	5.09E-02	4.88E-02	3.53E-02	3.39E-02	3.23E-02	3.00E-02

11.3 Additional Discussions

11.3.1 Discussing Influence of Transportation

Transportation of rocket parts was excluded in this assessment, but it is discussed here to show how transportation impacts can be relatively negligible compared to the rest of the rocket's lifetime impacts. Three transportation options are considered: air freight, rail freight, and truck. Each of their relative environmental impacts can be seen in Figure 57. Results are normalized for the impacts of transporting 1,000 kg a distance of 1 km.

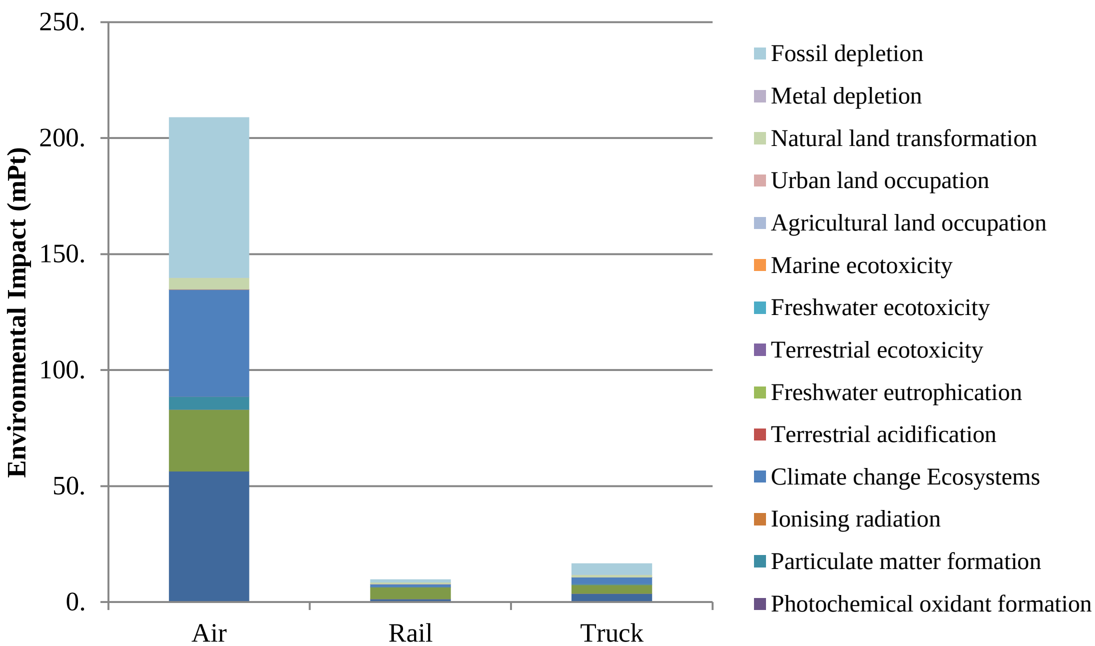


Figure 57: Relative impacts of transporting 1,000 kg a distance of 1 km using different means of transportation, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

Table 91: Comparing environmental impacts according to impact category when transporting 1,000 kg a distance of 1 km using different means of transportation, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 1)

Mode of Transportation	Climate change Human Health	Ozone depletion	Human toxicity	Photochemical oxidant formation	Particulate matter formation	Ionising radiation	Climate change Ecosystems	Terrestrial acidification
Air	5.63E+01	5.40E-03	2.65E+01	3.20E-03	5.52E+00	5.30E-03	4.60E+01	1.59E-01
Rail	1.31E+00	7.15E-05	5.01E+00	8.56E-05	2.28E-01	3.30E-03	1.07E+00	5.00E-03
Truck	3.54E+00	5.00E-04	3.76E+00	2.00E-04	3.78E-01	1.60E-03	2.90E+00	8.40E-03

Table 92: Comparing environmental impacts according to impact category when transporting 1,000 kg a distance of 1 km using different means of transportation, using the ReCiPe 2008 Egalitarian Endpoint single score indicator (Part 2)

Mode of Transportation	Freshwater eutrophication	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural land occupation	Urban land occupation	Natural land transformation	Metal depletion	Fossil depletion
Air	3.00E-03	9.97E-02	6.00E-04	2.40E-03	1.50E-02	7.42E-02	4.91E+00	3.50E-03	6.92E+01
Rail	1.60E-03	5.90E-03	2.00E-04	8.00E-04	1.17E-02	3.39E-02	7.36E-01	2.80E-03	1.44E+00
Truck	7.00E-04	3.62E-02	1.00E-04	5.00E-04	7.90E-03	3.19E-02	1.13E+00	3.20E-03	4.91E+00

The two stage, LOX/RP1 rocket with a lift capacity of 5,000 kg to LEO has a total lifetime environmental impact of about 234,720 Pts. The rocket has an inert mass of approximately 43,500 kg. The impacts of transporting the entire inert mass of the rocket 1 km are shown in Table 93. Also shown is the distance the entire inert mass of the rocket can be transported to add 1% to the rocket's lifetime impacts.

Table 93: Environmental impacts of transporting the 43,500 kg inert mass of the 2 stage, LOX/RP1 rocket capable of 5,000 kg to LEO a distance of 1 km and the distance the inert mass can be transported while contributing 1% to lifetime impacts, using the ReCiPe 2008 Egalitarian Endpoint impact assessment method

Mode of Transportation	Impacts for 1 km (Pt)	Distance (km)
Air	9.090	258
Rail	0.429	5,474
Truck	0.727	3,229

To put this in perspective, an entire Falcon 9 rocket (propellants excluded) can be transported by rail or truck from Los Angeles, California to Cape Canaveral, Florida (approximately 2,500 miles or 4,000 km) and the result would represent approximately 1% of the rocket's total impacts. This indicates that transportation may represent a non-negligible impact on the rocket's lifetime impacts, but this impact would be relatively small.

Including the propellants during transportation causes their impacts to go up significantly. The rocket described above has a total mass of roughly 400,000 kg. Transporting the entire rocket (including propellants) a distance of 4,000 km would represent roughly 7-12% of the rocket's entire lifetime impacts. This is appreciable, but it is still relatively small.

Transportation would become significant if it was assumed a significant portion of the rocket was transported by air freight.

11.3.2 Comparison to an Airplane's Life Cycle Impacts

A detailed LCA of an Airbus A330-200 was performed by (Lopes 2010). This analysis is extremely useful as a comparison when trying to determine the relative impacts of a rocket system. Lopes' approach to modeling the life cycle of the airplane was very similar to the approach taken in this research. The airplane was broken down into several major components, and each component was assigned a material and a manufacturing process. Lopes created the life cycle model in SimaPro, and performed the impact assessment using ReCiPe. The particular impact assessment method was the ReCiPe Midpoint Indicator from a Hierarchist perspective. The LCA model for the rocket was altered to use this same impact method.

The Airbus A330-200 has a maximum take-off mass of 242,000 kg, of which a maximum of 139,090 liters is fuel (112,663 kg when assuming Jet-A), and it has a range of approximately 13,400 km with 253 passengers on board. (Airbus 2013) According to calculations performed by (Lopes 2010), an average A330-200 consumes approximately 5,600 kg of Jet-A fuel per hour of operation. The non-fuel, non-cargo (passenger) mass of the aircraft is roughly 106,000 kg

By comparison, a 10,000 to LEO, two stage, LOX/RP1 rocket sized by the PRSM (without light-weighting) has a total mass of about 741,000 kg and a total fuel load (excluding oxidizer) of about 200,000 kg, and an inert mass of about 80,000 kg. This rocket is roughly equivalent to two Falcon 9 rocket. (SpaceX 2009)

The two vehicles are compared side by side in Table 94.

Table 94: Comparison of a LOX/RP1 rocket with a commercial airplane

	LOX/RP1 Rocket, 2 stage, 10,000 kg to LEO	Airbus A330-200
Inert Mass (kg)	80,000	106,000
Max Fuel Load (kg)	200,000	113,000
Gross Mass (kg)	741,000	242,000

The life cycle impacts of a single airplane were compared to those of a single rocket. This comparison is seen in Table 95.

It is seen that the structure of the airplane and the structure of the rocket are roughly comparable. There are certain impact categories where the airplane dominates, but others where the rocket dominates. However, when it comes to the use phases, the airplane dominates the rocket, overwhelmingly. Over its entire life cycle, the airplane has on the order of millions of times greater impact on the environment than the rocket.

Based on this analysis, rocket launches to LEO have a virtually negligible impact on global environmental impacts when compared to commercial aircraft.

Table 95: Comparison of the life cycle impacts by impact category of a single Airbus A330-200 to a single 10,000 kg to LEO, two stage, LOX/RP1 rocket over each vehicles entire lifetime, using the ReCiPe 2008 Egalitarian Midpoint impact assessment method

		A330-200			10,000 kg to LEO, Two Stage, LOX/RP1 Rocket			Ratio (Airplane:Rocket)		
Impact Category	**Unit**	**Structure**	**Use**	**Total**	**Structure**	**Use**	**Total**	**Structure**	**Use**	**Total**
Climate Change	kg CO2 eq	1.54E+06	3.29E+13	3.29E+13	3.23E+05	5.39E+05	8.62E+05	4.77E+00	6.10E+07	3.82E+07
Ozone Depletion	kg CFC-11 eq	0.00E+00	4.12E+06	4.12E+06	0.00E+00	0.00E+00	0.00E+00	2.56E+00	4.04E+07	2.94E+07
Human Toxicity	kg 1.4-DB eq	1.40E+05	6.73E+11	6.73E+11	7.95E+05	1.44E+05	9.38E+05	1.80E-01	4.68E+06	7.18E+05
Photochemical Oxidant Formation	kg NMVOC	4.78E+03	1.67E+11	1.67E+11	1.86E+03	1.10E+03	2.96E+03	2.56E+00	1.52E+08	5.65E+07
Particulate Matter Formation	kg PM10 eq	3.32E+03	4.31E+10	4.31E+10	2.51E+03	5.38E+02	3.05E+03	1.32E+00	8.01E+07	1.41E+07
Ionizing Radiation	kg U235 eq	3.32E+03	4.31E+10	2.09E+11	9.46E+04	1.60E+05	2.54E+05	4.00E-02	2.70E+05	8.23E+05
Terrestrial Acidification	kg SO2 eq	2.45E+05	2.09E+11	1.27E+11	8.76E+03	1.83E+03	1.06E+04	2.80E+01	1.14E+08	1.20E+07
Freshwater Eutrophication	kg P eq	1.09E+04	1.27E+11	1.12E+08	5.16E+02	2.02E+02	7.18E+02	2.11E+01	6.28E+08	1.56E+05
Marine Eutrophication	kg N eq	1.62E+02	1.12E+08	5.53E+10	6.30E+02	4.79E+02	1.11E+03	2.60E-01	2.34E+05	4.99E+07
Terrestrial Ecotoxicity	kg 1.4-DB eq	1.43E+03	5.53E+10	2.92E+10	1.12E+02	6.90E+01	1.81E+02	1.28E+01	8.00E+08	1.62E+08
Freshwater Ecotoxicity	kg 1.4-DB eq	1.88E+02	2.92E+10	1.45E+10	1.63E+04	3.20E+03	1.95E+04	1.00E-02	9.14E+06	7.45E+05
Marine Ecotoxicity	kg 1.4-DB eq	2.61E+03	1.45E+10	2.35E+10	1.71E+04	3.25E+03	2.04E+04	1.50E-01	4.47E+06	1.15E+06
Agricultural Land Occupation	m^2 a	2.20E+04	2.35E+10	1.65E+10	6.87E+03	2.74E+03	9.60E+03	3.21E+00	8.57E+06	1.72E+06
Urban Land Occupation	m^2 a	1.88E+04	1.65E+10	4.99E+10	4.80E+03	1.56E+03	6.36E+03	3.92E+00	1.06E+07	7.84E+06
Natural Land Transformation	m^2	4.62E+02	4.99E+10	1.65E+10	9.50E+01	3.86E+02	4.81E+02	4.88E+00	1.29E+08	3.44E+07
Water Depletion	m^3	1.36E+05	1.65E+10	3.89E+10	3.68E+03	2.37E+03	6.05E+03	3.69E+01	6.97E+06	6.43E+06
Metal Depletion	kg Fe eq	2.85E+05	3.89E+10	1.19E+11	4.41E+05	4.81E+03	4.46E+05	6.50E-01	8.08E+06	2.66E+05
Fossil Depletion	kg oil eq	4.62E+05	1.14E+13	1.14E+13	1.28E+05	3.09E+05	4.37E+05	3.62E+00	3.69E+07	2.61E+07

11.3.3 Suborbital Military Rockets

Suborbital and military rockets share much in common with the solid rockets in this assessment. It is expected that these smaller rockets would behave similarly when light-weighted with carbon fibers, at least in terms of environmental impacts. Though there may be some differences, the conclusion is that suborbital and military rockets that use solid propellants experience an increase in their overall life cycle environmental impacts when light-weighted with carbon fibers.

Though these rockets can be much smaller than orbit-capable rockets, they can be launched considerably more frequently. Environmental impacts from any individual launch may be almost negligible, but these small effects can add up across hundreds and thousands of launches. Literature can provide significant insight into this particular issue as the United States military has conducted LCA's on some of their most common rockets. Assessments performed specifically on the Patriot missile (PAC-3 Environmental Assessment Team 1997) and the MLRS rocket (Hubbard, 1998 #113) found that testing and operations relating to manufacturing and launching these rockets have no significant impact on the environment.

Though solid propelled rockets may be light-weighted for a number of reasons, improving environmental performance is not and should not be one of them.

11.3.4 Launch Frequency and Global Impact

According to (Federal Aviation Administration 2012), globally, there were 78 rocket launches to orbit in 2012. These 78 launches lifted the equivalent of approximately 700,000 kg of payload to LEO, making the average payload approximately 9,000 kg. These launches included commercial, military, and scientific payloads. Launches were conducted by nine different national entities, and thirty four different rocket configurations were used. Each of these thirty four rocket configurations used a combination of LOX/LH2, LOX/RP1, N2O4/UDMH, and solid propellant combinations, meaning that the LCA performed here provides insight into the environmental performance of all of these rockets.

Considering impacts shown in Table 95 as a reference, it would require many decades of launching rockets at the rates launched in 2012 to equal the environmental impacts of a single Airbus A330-200.

11.3.5 Discussion on the Space Shuttle

The NASA Space Transportation System, also known as the Orbital Space Shuttle, is possibly the most unique orbital launch rocket ever developed. A key feature that makes it so unique is that the Orbiter itself, which carries the crew and payload, is a reusable vehicle. Furthermore, the Space Shuttle Solid Rocket Boosters (SSSRB's) are reusable, meaning only the external propellant tank is discarded after each flight. (NASA 1988)

The solid propellant formulation assumed in this research is the same as the SSSRB's. In addition to solid boosters, the rocket uses LOX/LH2 propellants. Based on the results of the LCA on other, more typical rocket systems, the solid boosters have a high environmental impact, while the LOX/LH2 propulsion system would have a relatively low impact. Based on propellants, the analysis performed in this research indicates the Space Shuttle would have average environmental impacts when compared to other rockets with similar lift capacities to LEO. However, unlike other, simpler rockets, the space shuttle requires large, aerodynamic surfaces for its re-entry and landing. These surfaces increase the non-payload mass being lifted to LEO, indicating the Space Shuttle would have worse environmental impacts per kg payload to LEO than a more traditional rocket.

In theory, reusing such a large percentage of the Space Shuttle would reduce environmental impacts. However, extensive maintenance operations between launches (Wilhite 2012) can significantly increases the environmental impacts. According to (Lopes 2010), these maintenance operations can easily and significantly increase the Space Shuttle's environmental impacts, negating any environmental benefit gained from a reusable vehicle.

With respect to light-weighting, the Space Shuttle uses LOX/LH2 and solid propellants. This analysis showed that LOX/LH2 rockets do not benefit greatly from light-weighting, and there is a reasonable chance that light-weighting actually increases environmental impacts. This analysis also shows that light-weighting solid rockets is very likely to increase environmental impacts. It is concluded that the Space Shuttle would not be a good candidate for light-weighting.

Early in the Space Shuttle program, environmental assessments were performed specifically on launch operations. (Cicerone et al. 1973)(Hinkle and Knott III 1985) These concluded that there were noticeable impacts in the environment local to the launch pad, though it was concluded that there was no long-term damage. In a global sense, it was found that launch operations had a negligible impact due to their infrequency. Over a 30 year period, only 135 Space Shuttles were launched, where approximately 80 rockets were launched globally in 2012 alone (FAA 2013).

11.4 Chapter Summary

This chapter began by looking at alternate light-weighting scenarios. It was initially assumed that light-weighting reduces the mass of a component my 25%. It was assume in two additional scenarios that light-weighting reduces the mass of the component by as little as 10% and as much as 50%. It was found that in some cases, like the LOX/LH2 rocket and LOX/RP1 rocket, that if light-weighting only reduces the mass of a component by 10%, then the life cycle impacts are unchanged, or can actually increase. It was also found that if light-weighting can reduce the mass of components by 50%, then light-weighting the solid rocket may actually *reduce* lifetime impacts. Light-weighting the N2O4/UDMH rockets by any amount reduced lifetime impacts.

Next, the impact assessment was repeated using different methods. These include Eco-indicator 99, TRACI 2.0, CML 2000, and BEES. The results of using any of these impact assessment methods did not contradict or suggest that the original analysis using ReCiPe 2008 was misleading.

Transportation was then discussed. Transportation of material and parts was originally excluded from the analysis in Chapter 9. In this chapter, it was found that transporting an entire rocket, with its full propellant load, across the United States using either rail or truck would add about 7-12% to the rocket's life cycle impacts. This is a relatively small amount, though non-negligible, but it is not expected to influence any of the conclusions about light-weighting. Transportation of rocket components by air, however, could potentially become significant.

This chapter ends by putting the relative impacts of a rocket in perspective. A rocket is compared to an Airbus 330-200 airplane. It is found that the structure of the rocket and the structure of the airplane have impacts on the same order of magnitude. However, when it came to the use phase, the airplane's impacts were many orders of magnitude greater than the rocket. Looking at the rocket in a global sense with this perspective, rockets have a very small impact on the global environment. This does not imply that rocket's should be ignored, though.

12 CONCLUSION

12.1 Overview of Chapter Contents

This chapter provides an answer to the two research questions. This is followed up by a discussion of the contributions of this work. Finally, potential future work or expansion of the research performed here is discussed.

12.2 Answering the First Research Question

The first research question is repeated below.

> <u>Research Question 1:</u> *Does light-weighting a rocket with carbon fiber composites lead to a net reduction in lifetime environmental impacts?*

The answer to this question depends on the propellants being consumed by the rocket.

In the case of LOX/LH2 propellants, it is likely that light-weighting with carbon fiber composites reduces the lifetime environmental impacts of a rocket, though there are reasonable scenarios where light-weighting does not have a net reduction in impacts. Given reasonable amounts of error in some of the mass calculations and inventories, it was found that there are scenarios where light-weighting can actually be worse for the environment. For these propellants, the answer to the first research question is ***yes***, but with a low level of confidence.

In the case of LOX/RP1 propellants, light-weighting with carbon fiber composites almost certainly reduces lifetime environmental impacts. It was found that in some extreme cases that if light-weighting reduces the mass of certain components by less than a certain amount, lifetime environmental impacts actually increase. These cases are at the extreme ends of the analysis, so the likelihood of light-weighting increasing the impacts of a LOX/RP1 rocket is quite small. For these propellants, the answer to the first research question is ***yes***, with a high level of confidence.

In the case of the N2O4/UDMH rocket, it was found that light-weighting with carbon fiber composites always reduced lifetime environmental impacts. Even at the extreme ends of error and light-weighting scenarios, a reduction was seen in lifetime impacts. For these propellants, the answer to the first research question is ***yes***, with an extremely high level of confidence.

In the case of solid propellant, it was found that light-weighting with carbon fiber composites likely *increased* lifetime environmental impacts. However, in some cases of extreme error and light-weighting potential, it was found that lifetime impacts can actually be reduced. The likelihood of this being the case is low, but not negligible. For this propellant, the answer to the first research question is ***no***, with a moderate level of confidence.

Based on the behavior or automobiles and airplanes, the initial prediction was that light-weighting would reduce the rocket's lifetime environmental impacts by reducing the amount of propellant that is consumed during its life. The benefit would come from not having to burn the added propellants. On the one hand, it was found to be the case that the greatest benefit of light-weighting was related to reducing the required propellant load of the rocket, partially supporting the initial prediction. This was found to be the case even in rockets whose lifetime impacts are dominated by the structure and not the propellants. On the other hand, it was found that the environmental benefit was on account of not having to produce the propellants in the first place, rather than not having to burn them during launch. This does not support part of the initial prediction because it indicates that the benefits of light-weighting are upstream in the material harvesting and manufacturing phases, rather than in the use phase as with automobiles and airplanes.

The answer to the first research question is summarized in Table 96.

Table 96: Summary of answers to the first research question, which asks whether light-weighting a rocket with carbon fiber reinforced polymers reduces lifetime environmental impacts, giving confidence of conclusion

Propellant Combination	Reduced Impacts?	Confidence
LOX/LH2	yes	low
LOX/RP1	yes	high
N2O4/UDMH	yes	high
Solid	no	moderate

12.3 Answering the Second Research Question

The second research question is repeated here.

> <u>*Research Question 2:*</u> *How does the relationship between light-weighing with carbon fiber composites and environmental impacts change when different rocket configurations are considered?*

As discussed in the previous section, the relationship between light-weighting with carbon fiber composites and the lifetime environmental impacts of a rocket can change, depending on the propellant combination used. Light-weighting is likely to reduce lifetime impacts, but there are certain scenarios with certain propellants where this is not the case.

It was found that light-weighting rockets of different sizes, or different lift capacities, slightly changed the magnitude of the effects of light-weighting but did not change their direction. In other words, light-weighting a smaller rocket as opposed to a larger rocket of similar type would perhaps change how much the rocket's impacts are reduced, but it would not change the impacts such that they will not be reduced but will actually increase.

It was found that the number of stages a rocket uses is extremely important to determining its environmental impacts. Light-weighting a two stage liquid propellant rocket will reduce lifetime impacts on the order of 5%. Increasing the number of stages of that rocket from two to three stages reduces lifetime impacts on the order of 25%, a five-fold difference over the reduction of light-weighting.

It is concluded that while light-weighting may or may not reduce lifetime environmental impacts of a rocket, increasing the number of stages of the rocket will certainly reduce environmental impacts.

12.4 General Conclusions About Research

This research found that the environmental impacts of a rocket are most significantly affected by propellant selection. Even though certain rockets were found to have their lifetime impacts dominated by their inert structure, changes in environmental impacts due to light-weighting, different lift capacities, and different number of stages tend to be the related to the propellants more so than the structure. This is especially true for liquid propellant rockets.

It was also found in this research that light-weighting a rocket using CFRP's results in a relatively small change in a rocket's lifetime environmental impacts. Though it was found that liquid propellant rockets were likely to reduce environmental impacts with light-weighting and solid rockets were likely to increase impacts, this change was on the order of 1-3%. In terms of reducing environmental impacts, increasing the number of stages the rocket uses has a much greater (20-30%) reduction in environmental impacts, even when light-weighting is not included. Should reducing the environmental impacts of rockets become an important concern, it would be better to design rockets with more stages than to design rockets with light-weight CFRP components.

It was also found that the environmental impacts of rockets are virtually negligible when compared to the impacts of a commercial airplane. Whereas a rocket is a single use system, an airplane can fly tens of thousands of flights, each consuming on the order of the same amount of fuel as a rocket with similar structural mass. Furthermore, an airplane undergoes regular maintenance where many components can be replaced over the course of its life, increasing its use phase impacts. Nevertheless, rockets are still subject to environmental problems, such as resource scarcity, even though they are not the cause of these environmental issues.

12.5 Research Contribution

The contributions of this research are listed below.

- Determined that light-weighting does not always reduce environmental impacts, which was not expected
- First to investigate lifetime environmental impacts of a broad range of rocket configurations
- Determined parts of the rocket's life cycle that drive lifetime environmental impacts
- Developed a parametric rocket sizing model that can be used in preliminary rocket sizing
- Developed a carbon fiber production model that can (and was used to) calculate case-specific energy consumption during fiber production
- Created a parametric life cycle model of a rocket in SimaPro that can be used as a basis for future life cycle assessments on rockets

This research represents the first known environmental life cycle assessment performed on a general series of rockets, and not one unique rocket. Assessing a wide range of rockets, considering different propellants, number of stages, and lift capacities, this research was able to uncover general trends that indicate the environmental effectiveness of light-weighting a rocket with carbon fiber composites.

During the course of this research, several models were developed and used. These include the Carbon Fiber Production Model, the Parametric Rocket Sizing Model, and the Rocket Life Cycle Assessment Model in SimaPro. These provide a baseline and a framework upon which future research can be built. This is important academically as no such models were found in literature meaning that what is developed here can serve as a baseline or a starting point upon which future investigations can be compared to or built upon. The models developed here can be expanded and evolve into higher fidelity assessments that can predict real world performance more accurately.

A leading contribution of this research is that it is the first to thoroughly assess the environmental impacts of an orbital launch rocket. The analysis considered multiple different propellants, lift capacities, and staging options, conclusively developing a relationship between these design parameters and environmental impacts. No such analysis is found in any existing literature, and this research can serve as a solid benchmark for determining the environmental impacts of different rockets.

This research showed that a rocket's lifetime environmental impact is not necessarily dominated by the use phase, as would be expected based on experience with airplanes and automobiles. When considering certain propellants, the rocket's lifetime impacts were found to be dominated by the structure and not the propellants. This is an important finding for industry as impacts associated with harvesting materials for and manufacturing the structure of the rocket are felt *in-house* rather than at some remote launch site or down range.

This research also showed that there is a greater environmental benefit from increasing the number of stages a rocket uses than by light-weighting certain components. Should the industry come under more strict environmental regulation, this conclusion shows that efforts should be spent designing rockets with a greater number of stages, rather than changing the material composition of the rocket.

The greatest contribution of this research is that it provides strong evidence to support that rockets do not behave similarly to other, more common systems in response to light-weighting. It is shown that a rocket's life cycle is not always dominated by propellants, a rocket's impacts are not dominated by its use phase but by material harvesting and manufacturing, and a rocket's lifetime impacts do not always decrease when light-weighted.

12.6 Potential Future Work

There is great potential for this research to be expanded and continued. The rocket can be modeled in greater detail, increasing the accuracy and fidelity of the results. Additional scenarios can also be considered, providing insight into a greater variety of real world rockets. Continuing this research can be useful for both academia and industry. Academically, this research can help formulate methods for modeling and assessing large, atypical systems. For industry, such models can be expanded to include life cycle assessments that go beyond looking at environmental considerations.

APPENDIX A: ESTIMATING RELATIONSHIPS

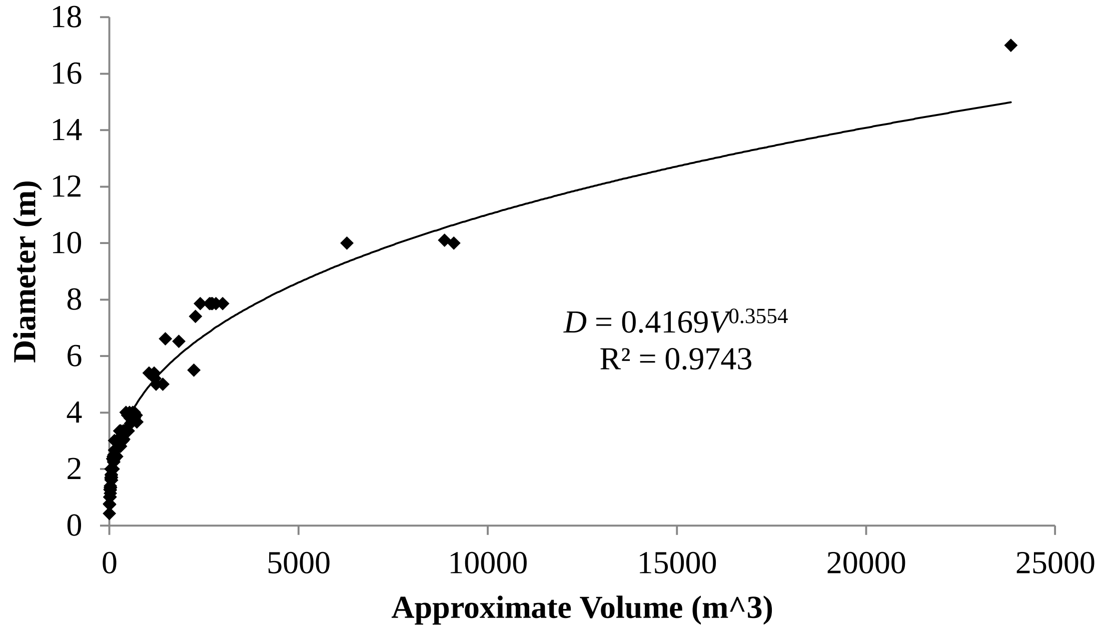


Figure A 1: Rocket diameter as a function of approximate cylinder volume

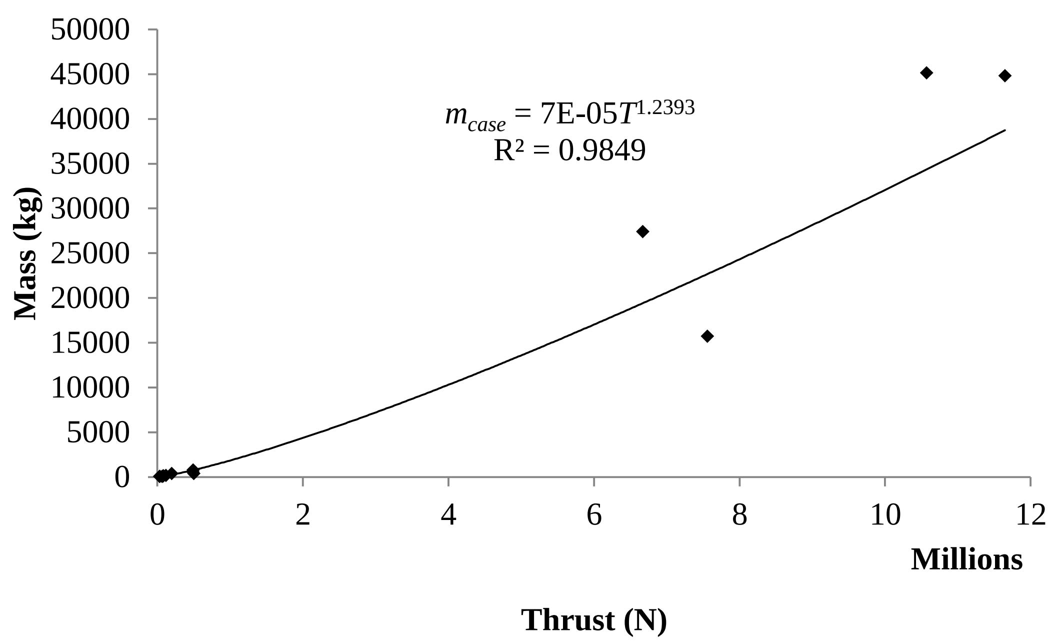


Figure A 2: Solid motor case mass as a function of motor thrust

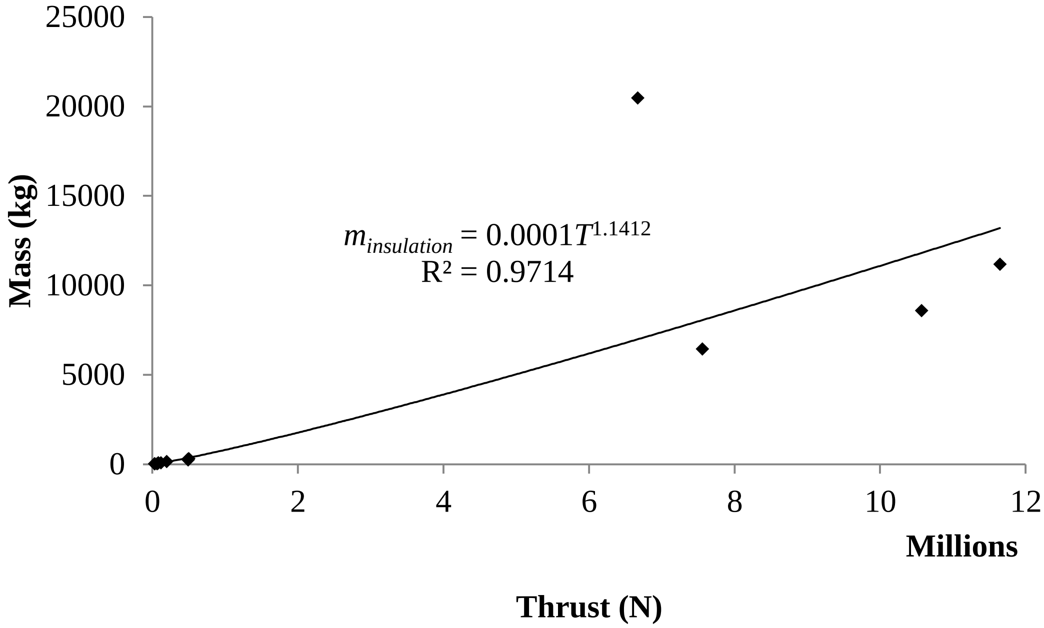


Figure A 3: Solid motor insulation mass as a function of motor thrust

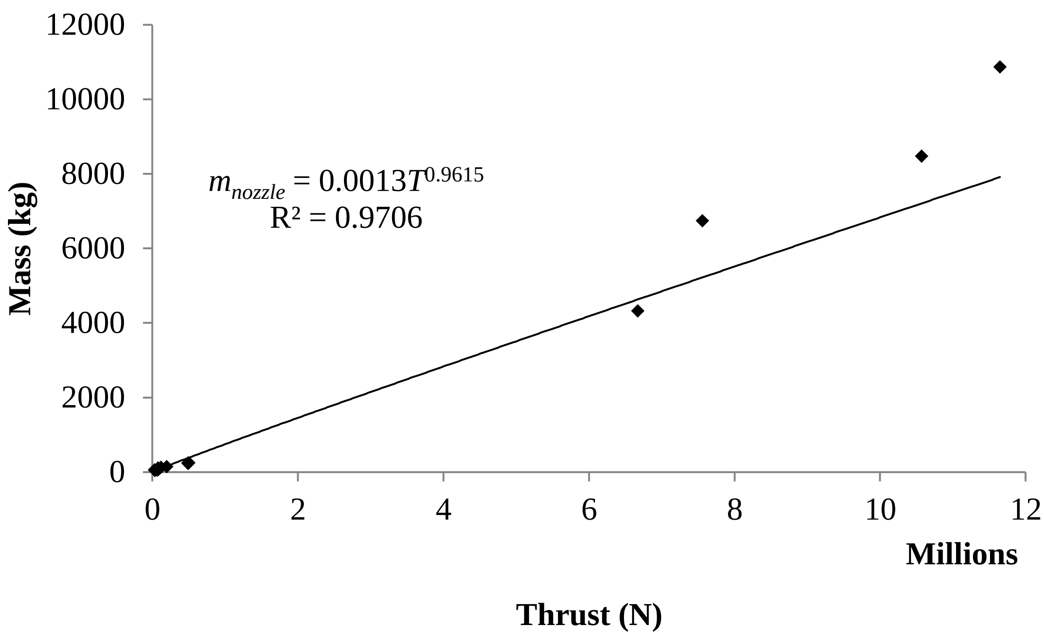


Figure A 4: Solid motor nozzle mass as a function of motor thrust

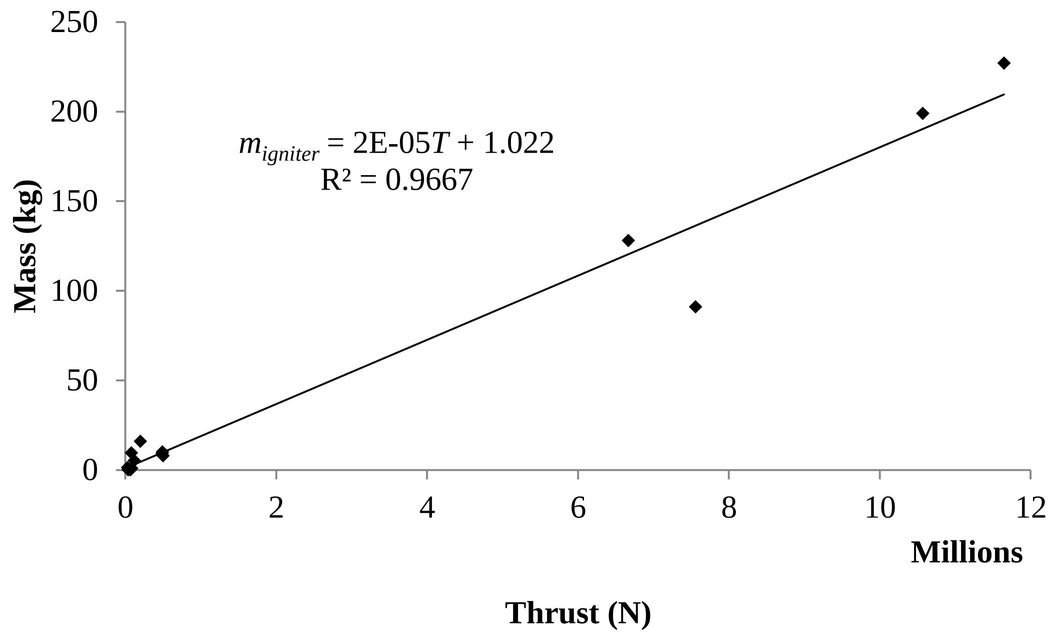


Figure A 5: Solid motor igniter mass as a function of motor thrust

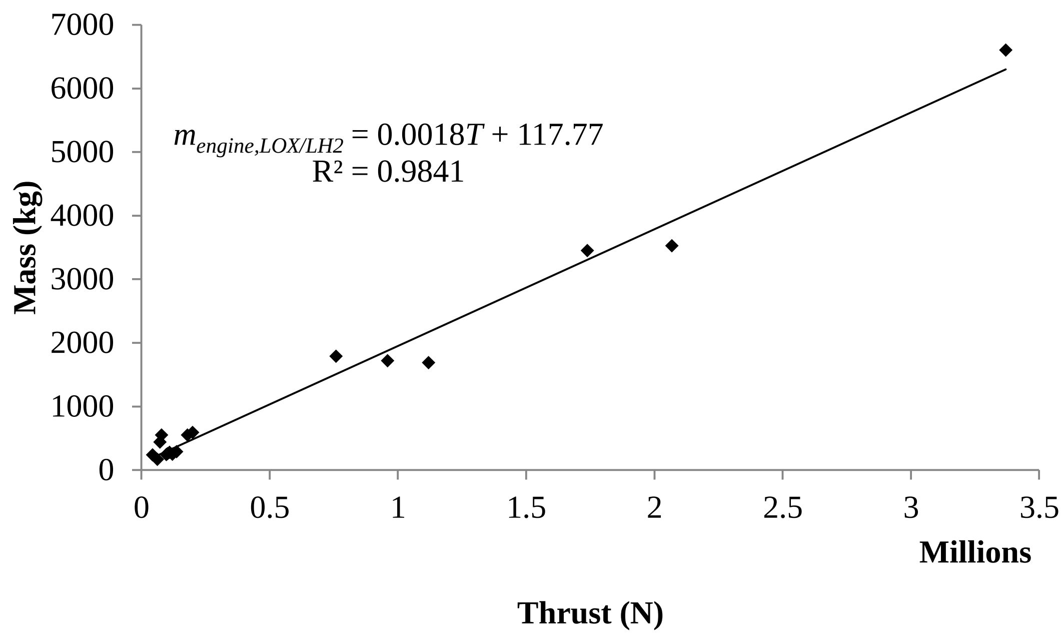


Figure A 6: Mass of a LOX/LH2 engine as a function of engine thrust

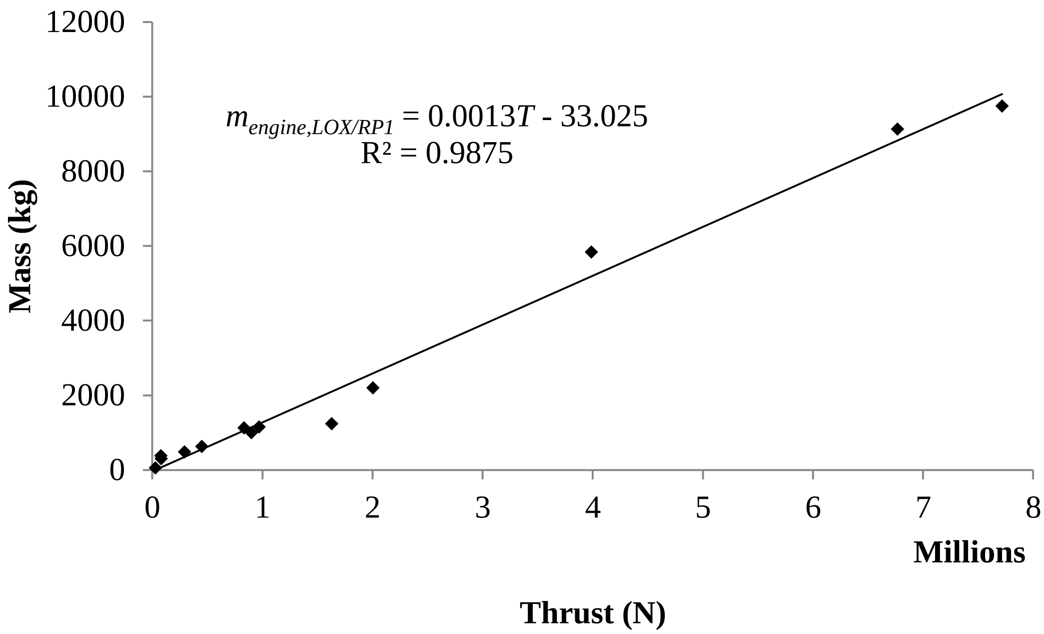


Figure A 7: Mass of a LOX/RP1 engine as a function of engine thrust

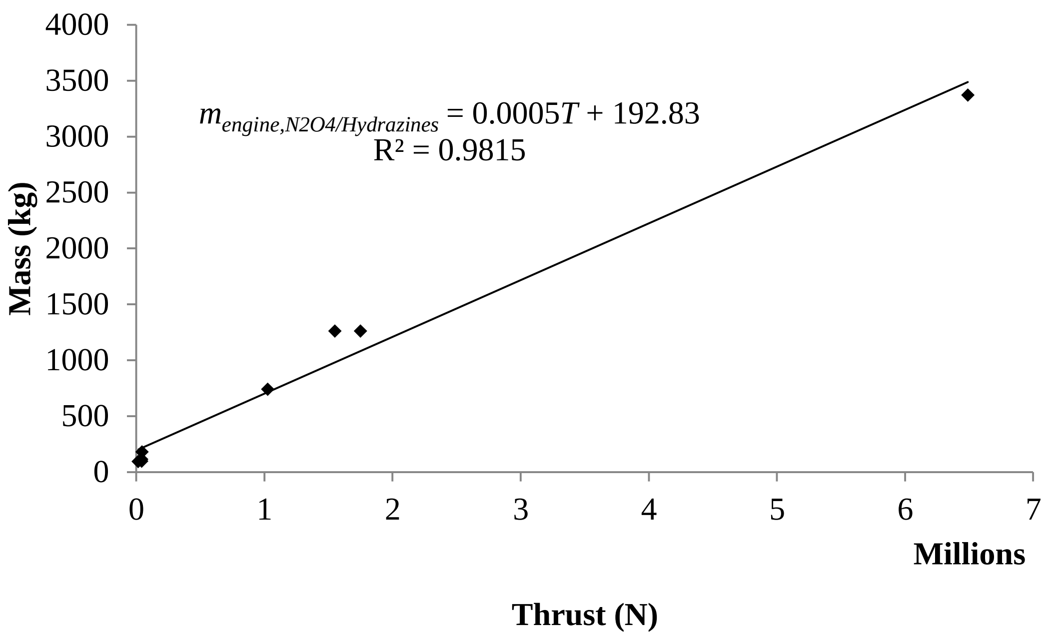


Figure A 8: Mass of an N2O4/UDMH engine as a function of engine thrust

Table A 1: Mass Estimating Relationships according to literature (Wilhite 2012)

Fuel Tank	$0.3955V_{tank}^{1.063}$
Oxidizer Tank	$1.2429V_{tank}^{0.9383}$
Fore Inter-Stage Adapter	$6.912A_{base}^{1.2053}$
Aft Inter-Stage Adapter	$6.912A_{base}^{1.2053}$
Inter-Tank Adapter	$6.912A_{base}^{1.2053}$
Aft Skirt	$6.912A_{base}^{1.2053}$
Thrust Structure	$8.969\text{x}10^{-5}T^{1.068}$
Payload Fairing	$0.2m_{pl}$
Fuel Tank Insulation	$1.95A_{surface,tank}$
Oxidizer Tank Insulation	$1.95A_{surface,tank}$
Base Heat Shield	$2.1A_{base}$
Propellant Feed Lines	$1.52\text{x}10^{-4}m_{prop}$
Gimbal	$7.5\text{x}10^{-4}T$
RCS Engines	$6.7\text{x}10^{-3}m_{tot}$
RCS Oxidizer Tank	$1.2429V_{prop,RCS}^{0.9383}$
RCS Fuel Tank	$0.3955V_{prop,RCS}^{1.063}$
RCS Propellant Feed Lines	$1.52\text{x}10^{-4}m_{prop,RCS}$
Guidance Navigation	243 kg
Communication and Tracking	359 kg
Data Processing	61 kg
Thermal Control System	294 kg
Ordinance	19 kg
Main Propellant Residuals	$0.018m_{prop}$
Main Propellant Reserves	$0.02m_{prop}$
Main Prop. Pressurant - He	$33.23V_{prop}$
RCS Residuals	$0.018m_{prop,RCS}$
RCS Reserves	$0.02m_{prop,RCS}$
RCS Pressurant - He	$33.23V_{prop,RCS}$

APPENDIX B: PARAMETRIC ROCKET SIZING MODEL RESULTS

Table B 1: Baseline Parametric Rocket Sizing Model results for the two stage, LOX/LH2 rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	2,500.0	5,000.0	10,000.0	20,000.0	35,000.0
Stage 2	Fuel Tank	16.4	29.1	55.4	109.8	194.1
	Oxidizer Tank	12.2	20.2	35.6	65.1	107.6
	Fore Inter-Stage Adapter	16.2	25.8	43.3	75.1	118.9
	Inter-Tank Adapter	16.2	25.8	43.3	75.1	118.9
	Thrust Structure	65.1	115.9	220.9	439.2	778.5
	Payload Fairing	500.0	1,000.0	2,000.0	4,000.0	7,000.0
	Fuel Tank Insulation	166.6	236.4	349.4	529.8	749.4
	Oxidizer Tank Insulation	60.4	85.8	127.2	193.3	274.1
	Base Heat Shield	4.3	6.3	9.6	15.2	22.3
	Main Engines	670.7	1,067.1	1,855.0	3,423.0	5,767.0
	Main Propellant Feed Lines	2.3	4.0	7.3	13.9	23.8
	Gimbal	230.4	395.6	723.8	1,377.2	2,353.8
	RCS Engines	155.5	266.9	488.4	929.3	1,588.3
	RCS Oxidizer Tank	0.2	0.4	0.7	1.2	2.0
	RCS Fuel Tank	0.3	0.5	0.8	1.5	2.5
	RCS Propellant Feed Lines	0.1	0.1	0.2	0.4	0.6
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	275.8	473.5	866.4	1,648.5	2,817.6
	Main Propellant Reserves	306.4	526.1	962.7	1,831.7	3,130.7
	Main Propellant Pressurant - He	1,483.0	2,546.4	4,659.5	8,865.4	15,152.3
	RCS Propellant	398.5	684.2	1,251.9	2,382.0	4,071.1
	RCS Resuduals	7.2	12.3	22.5	42.9	73.3
	RCS Reserves	8.0	13.7	25.0	47.6	81.4
	RCS Pressurant - He	12.2	21.0	38.4	73.0	124.7
	Stage 2 Total Inert Mass	**5,383.8**	**8,532.9**	**14,763.5**	**27,116.1**	**45,528.8**
	Fuel	2,357.0	4,047.0	7,405.5	14,090.0	24,082.0
	Oxidizer	12,963.5	22,258.5	40,730.0	77,494.8	132,450.8
	Stage 2 Total Propellant Mass	**15,320.5**	**26,305.5**	**48,135.5**	**91,584.8**	**156,532.7**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**23,204.3**	**39,838.4**	**72,899.0**	**138,700.9**	**237,061.5**
	Fuel Tank	88.9	156.8	296.2	584.3	1,030.0
	Oxidizer Tank	54.0	89.1	156.3	284.6	469.5
	Fore Inter-Stage Adapter	63.4	100.1	167.2	289.0	456.5
	Aft Skirt	63.4	100.1	167.2	289.0	456.5
	Inter-Tank Adapter	63.4	100.1	167.2	289.0	456.5
	Thrust Structure	355.3	628.2	1,190.6	2,355.8	4,164.1
	Fuel Tank Insulation	465.9	658.0	969.4	1,465.8	2,070.2
	Oxidizer Tank Insulation	169.9	240.5	355.1	538.5	762.4
	Base Heat Shield	13.2	19.3	29.5	46.5	67.9
	Main Engines	2,827.9	4,739.0	8,527.1	16,049.5	27,276.3
	Propellant Feed Lines	11.4	19.5	35.4	67.1	114.4
	Gimbal	1,129.2	1,925.5	3,503.9	6,638.2	11,316.1
	Main Propellant Residuals	1,351.7	2,304.9	4,194.2	7,946.1	13,545.6
	Main Propellant Reserves	1,501.9	2,561.0	4,660.2	8,829.0	15,050.7
	Main Propellant Pressurant - He	7,269.1	12,395.2	22,555.6	42,732.4	72,845.1
	Stage 1 Total Inert Mass	**15,428.5**	**26,037.3**	**46,975.1**	**88,404.9**	**150,081.6**
	Fuel	11,552.9	19,700.0	35,848.1	67,915.5	115,774.3
	Oxidizer	63,541.2	108,350.0	197,164.4	373,535.3	636,758.7
	Stage 1 Total Propellant Mass	**75,094.2**	**128,050.0**	**233,012.5**	**441,450.9**	**752,533.1**
	Total Rocket Propellant Mass	**90,414.7**	**154,355.4**	**281,148.0**	**533,035.7**	**909,065.8**
	Total Rocket Inert Mass	**20,812.3**	**34,570.2**	**61,738.5**	**115,521.0**	**195,610.4**
	Total Rocket Mass	**113,727.0**	**193,925.7**	**352,886.5**	**668,556.7**	**1,139,676.2**

Table B 2: Baseline Parametric Rocket Sizing Model results for the two stage, LOX/LH2 rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	**50,000.0**	**75,000.0**	**100,000.0**	**150,000.0**	**200,000.0**
Stage 2	Fuel Tank	280.5	427.7	578.0	884.8	1,197.9
	Oxidizer Tank	148.9	216.2	281.9	410.6	536.4
	Fore Inter-Stage Adapter	160.0	224.8	286.5	403.8	515.5
	Inter-Tank Adapter	160.0	224.8	286.5	403.8	515.5
	Thrust Structure	1,127.0	1,722.1	2,330.2	3,574.2	4,846.1
	Payload Fairing	10,000.0	15,000.0	20,000.0	30,000.0	40,000.0
	Fuel Tank Insulation	937.7	1,212.3	1,456.1	1,887.1	2,269.5
	Oxidizer Tank Insulation	343.4	444.8	534.9	694.5	836.3
	Base Heat Shield	28.5	37.7	46.2	61.4	75.1
	Main Engines	8,106.1	11,998.9	15,887.3	23,656.9	31,420.4
	Main Propellant Feed Lines	33.6	50.0	66.4	99.1	131.8
	Gimbal	3,328.5	4,950.5	6,570.7	9,808.0	13,042.8
	RCS Engines	2,246.0	3,340.5	4,433.7	6,618.2	8,801.0
	RCS Oxidizer Tank	2.8	4.1	5.3	7.8	10.2
	RCS Fuel Tank	3.4	4.9	6.4	9.3	12.2
	RCS Propellant Feed Lines	0.9	1.3	1.7	2.6	3.4
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	3,984.3	5,925.8	7,865.2	11,740.4	15,612.5
	Main Propellant Reserves	4,426.9	6,584.2	8,739.2	13,044.8	17,347.3
	Main Propellant Pressurant - He	21,426.4	31,867.7	42,297.4	63,136.9	83,960.5
	RCS Propellant	5,756.8	8,562.2	11,364.5	16,963.6	22,558.5
	RCS Resuduals	103.6	154.1	204.6	305.3	406.1
	RCS Reserves	115.1	171.2	227.3	339.3	451.2
	RCS Pressurant - He	176.4	262.4	348.2	519.8	691.2
	Stage 2 Total Inert Mass	**63,872.9**	**94,364.3**	**124,794.3**	**185,548.3**	**246,217.6**
	Fuel	34,053.4	50,648.0	67,224.2	100,345.0	133,440.4
	Oxidizer	187,293.9	278,564.2	369,733.3	551,897.4	733,922.4
	Stage 2 Total Propellant Mass	**221,347.3**	**329,212.2**	**436,957.6**	**652,242.4**	**867,362.8**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**335,220.2**	**498,576.5**	**661,751.9**	**987,790.7**	**1,313,580.4**
	Fuel Tank	1,486.6	2,263.9	3,056.5	4,674.8	6,326.0
	Oxidizer Tank	649.1	940.9	1,226.4	1,784.4	2,330.6
	Fore Inter-Stage Adapter	613.5	861.1	1,096.8	1,544.7	1,971.2
	Aft Skirt	613.5	861.1	1,096.8	1,544.7	1,971.2
	Inter-Tank Adapter	613.5	861.1	1,096.8	1,544.7	1,971.2
	Thrust Structure	6,020.1	9,186.3	12,420.0	19,033.8	25,793.4
	Fuel Tank Insulation	2,588.4	3,344.1	4,015.0	5,201.0	6,253.4
	Oxidizer Tank Insulation	954.8	1,235.9	1,485.8	1,928.5	2,322.1
	Base Heat Shield	86.8	115.0	140.6	186.8	228.6
	Main Engines	38,470.1	57,087.7	75,676.8	112,807.4	149,901.3
	Propellant Feed Lines	161.5	239.9	318.2	474.6	630.9
	Gimbal	15,980.1	23,737.5	31,482.9	46,954.0	62,409.8
	Main Propellant Residuals	19,128.6	28,414.3	37,685.8	56,205.1	74,706.1
	Main Propellant Reserves	21,254.0	31,571.5	41,873.2	62,450.1	83,006.7
	Main Propellant Pressurant - He	102,869.3	152,805.7	202,665.7	302,258.0	401,751.8
	Stage 1 Total Inert Mass	**211,489.9**	**313,526.1**	**415,337.4**	**618,592.9**	**821,574.3**
	Fuel	163,492.5	242,857.5	322,101.2	480,385.6	638,513.5
	Oxidizer	899,208.6	1,335,716.5	1,771,556.8	2,642,120.6	3,511,824.0
	Stage 1 Total Propellant Mass	**1,062,701.1**	**1,578,574.1**	**2,093,658.0**	**3,122,506.2**	**4,150,337.4**
	Total Rocket Propellant Mass	**1,284,048.4**	**1,907,786.3**	**2,530,615.6**	**3,774,748.6**	**5,017,700.2**
	Total Rocket Inert Mass	**275,362.8**	**407,890.4**	**540,131.7**	**804,141.1**	**1,067,792.0**
	Total Rocket Mass	**1,609,411.2**	**2,390,676.7**	**3,170,747.3**	**4,728,889.7**	**6,285,492.2**

Table B 3: Light-Weighted Parametric Rocket Sizing Model results for the two stage, LOX/LH2 rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	**2,500.0**	**5,000.0**	**10,000.0**	**20,000.0**	**35,000.0**
Stage 2	Fuel Tank	15.9	28.0	53.1	105.0	185.5
	Oxidizer Tank	11.8	19.5	34.3	62.6	103.4
	Fore Inter-Stage Adapter	11.8	18.7	31.4	54.4	86.0
	Inter-Tank Adapter	11.8	18.7	31.4	54.4	86.0
	Thrust Structure	62.9	111.4	211.7	420.0	743.9
	Payload Fairing	375.0	750.0	1,500.0	3,000.0	5,250.0
	Fuel Tank Insulation	163.2	230.8	340.5	515.6	729.0
	Oxidizer Tank Insulation	59.1	83.8	123.9	188.1	266.6
	Base Heat Shield	4.2	6.1	9.4	14.8	21.6
	Main Engines	653.3	1,032.5	1,786.7	3,287.8	5,531.9
	Main Propellant Feed Lines	2.3	3.9	7.0	13.4	22.8
	Gimbal	223.1	381.2	695.4	1,320.9	2,255.9
	RCS Engines	150.6	257.2	469.2	891.3	1,522.2
	RCS Oxidizer Tank	0.2	0.4	0.6	1.2	2.0
	RCS Fuel Tank	0.3	0.4	0.8	1.4	2.4
	RCS Propellant Feed Lines	0.1	0.1	0.2	0.3	0.6
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	267.1	456.3	832.4	1,581.1	2,700.3
	Main Propellant Reserves	296.8	506.9	924.9	1,756.8	3,000.4
	Main Propellant Pressurant - He	1,436.4	2,453.6	4,476.4	8,502.8	14,521.8
	RCS Propellant	385.9	659.2	1,202.7	2,284.5	3,901.7
	RCS Resuduals	6.9	11.9	21.6	41.1	70.2
	RCS Reserves	7.7	13.2	24.1	45.7	78.0
	RCS Pressurant - He	11.8	20.2	36.9	70.0	119.6
	Stage 2 Total Inert Mass	**5,134.3**	**8,040.0**	**13,790.5**	**25,189.3**	**42,177.7**
	Fuel	2,282.9	3,899.6	7,114.5	13,513.7	23,079.8
	Oxidizer	12,555.9	21,447.7	39,129.8	74,325.6	126,939.1
	Stage 2 Total Propellant Mass	**14,838.8**	**25,347.3**	**46,244.3**	**87,839.4**	**150,018.9**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**22,473.1**	**38,387.4**	**70,034.8**	**133,028.6**	**227,196.6**
	Fuel Tank	85.8	150.5	283.5	558.1	983.2
	Oxidizer Tank	52.3	86.0	150.3	273.4	450.6
	Fore Inter-Stage Adapter	46.2	72.6	121.0	208.9	329.8
	Aft Skirt	46.2	72.6	121.0	208.9	329.8
	Inter-Tank Adapter	46.2	72.6	121.0	208.9	329.8
	Thrust Structure	342.8	602.8	1,139.0	2,249.8	3,974.0
	Fuel Tank Insulation	455.9	641.8	943.7	1,425.5	2,012.3
	Oxidizer Tank Insulation	166.2	234.5	345.7	523.6	740.9
	Base Heat Shield	12.9	18.8	28.7	45.1	65.8
	Main Engines	2,738.4	4,564.2	8,185.4	15,377.7	26,113.3
	Propellant Feed Lines	11.0	18.7	34.0	64.3	109.5
	Gimbal	1,091.9	1,852.7	3,361.5	6,358.3	10,831.5
	Main Propellant Residuals	1,307.1	2,217.7	4,023.8	7,611.0	12,965.5
	Main Propellant Reserves	1,452.3	2,464.1	4,470.9	8,456.7	14,406.1
	Main Propellant Pressurant - He	7,029.2	11,926.2	21,639.1	40,930.4	69,725.6
	Stage 1 Total Inert Mass	**14,884.5**	**24,995.8**	**44,968.4**	**84,500.8**	**143,367.7**
	Fuel	11,171.7	18,954.6	34,391.5	65,051.7	110,816.5
	Oxidizer	61,444.3	104,250.3	189,153.1	357,784.3	609,490.5
	Stage 1 Total Propellant Mass	**72,616.0**	**123,204.9**	**223,544.6**	**422,836.0**	**720,307.0**
	Total Rocket Propellant Mass	**87,454.8**	**148,552.3**	**269,788.9**	**510,675.4**	**870,325.9**
	Total Rocket Inert Mass	**20,018.7**	**33,035.8**	**58,759.0**	**109,690.0**	**185,545.4**
	Total Rocket Mass	**109,973.5**	**186,588.1**	**338,547.8**	**640,365.4**	**1,090,871.3**

Table B 4: Light-Weighted Parametric Rocket Sizing Model results for the two stage, LOX/LH2 rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	50,000.0	75,000.0	100,000.0	150,000.0	200,000.0
Stage 2	Fuel Tank	268.0	408.6	552.1	845.0	1,144.0
	Oxidizer Tank	143.1	207.6	270.7	394.2	515.1
	Fore Inter-Stage Adapter	115.7	162.5	207.1	291.9	372.6
	Inter-Tank Adapter	115.7	162.5	207.1	291.9	372.6
	Thrust Structure	1,076.7	1,644.8	2,225.2	3,413.0	4,627.2
	Payload Fairing	7,500.0	11,250.0	15,000.0	22,500.0	30,000.0
	Fuel Tank Insulation	912.1	1,179.0	1,416.0	1,835.0	2,206.8
	Oxidizer Tank Insulation	334.0	432.5	520.1	675.2	813.1
	Base Heat Shield	27.6	36.6	44.8	59.5	72.9
	Main Engines	7,771.4	11,498.5	15,221.6	22,660.9	30,094.7
	Main Propellant Feed Lines	32.2	47.9	63.6	94.9	126.3
	Gimbal	3,189.0	4,742.0	6,293.3	9,393.0	12,490.4
	RCS Engines	2,151.9	3,199.8	4,246.6	6,338.2	8,428.2
	RCS Oxidizer Tank	2.7	3.9	5.1	7.5	9.8
	RCS Fuel Tank	3.3	4.7	6.2	9.0	11.7
	RCS Propellant Feed Lines	0.8	1.2	1.7	2.5	3.3
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	3,817.3	5,676.3	7,533.2	11,243.6	14,951.3
	Main Propellant Reserves	4,241.5	6,307.0	8,370.2	12,492.9	16,612.5
	Main Propellant Pressurant - He	20,528.6	30,525.6	40,511.7	60,465.5	80,404.6
	RCS Propellant	5,515.6	8,201.6	10,884.7	16,245.9	21,603.1
	RCS Resuduals	99.3	147.6	195.9	292.4	388.9
	RCS Reserves	110.3	164.0	217.7	324.9	432.1
	RCS Pressurant - He	169.0	251.3	333.5	497.8	662.0
	Stage 2 Total Inert Mass	**59,101.8**	**87,231.6**	**115,304.1**	**171,350.6**	**227,318.9**
	Fuel	32,626.6	48,515.0	64,386.2	96,099.2	127,788.8
	Oxidizer	179,446.5	266,832.6	354,124.2	528,545.6	702,838.4
	Stage 2 Total Propellant Mass	**212,073.2**	**315,347.6**	**418,510.4**	**624,644.8**	**830,627.2**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**321,174.9**	**477,579.2**	**633,814.5**	**945,995.3**	**1,257,946.1**
	Fuel Tank	1,418.6	2,160.0	2,916.0	4,459.7	6,034.8
	Oxidizer Tank	622.8	902.7	1,176.5	1,711.7	2,235.6
	Fore Inter-Stage Adapter	443.1	621.8	792.0	1,115.4	1,423.3
	Aft Skirt	443.1	621.8	792.0	1,115.4	1,423.3
	Inter-Tank Adapter	443.1	621.8	792.0	1,115.4	1,423.3
	Thrust Structure	5,743.6	8,762.7	11,846.4	18,153.7	24,600.5
	Fuel Tank Insulation	2,515.6	3,249.8	3,901.5	5,053.9	6,076.4
	Oxidizer Tank Insulation	927.7	1,200.7	1,443.5	1,873.5	2,255.8
	Base Heat Shield	84.1	111.5	136.2	181.0	221.6
	Main Engines	36,818.3	54,624.3	72,404.3	107,921.2	143,405.2
	Propellant Feed Lines	154.6	229.6	304.5	454.0	603.5
	Gimbal	15,291.9	22,711.1	30,119.4	44,918.1	59,703.1
	Main Propellant Residuals	18,304.8	27,185.7	36,053.7	53,768.1	71,466.1
	Main Propellant Reserves	20,338.6	30,206.3	40,059.6	59,742.3	79,406.7
	Main Propellant Pressurant - He	98,438.8	146,198.4	193,888.2	289,152.1	384,327.9
	Stage 1 Total Inert Mass	**201,988.7**	**299,408.3**	**396,625.7**	**590,735.3**	**784,607.0**
	Fuel	156,451.0	232,356.4	308,150.9	459,556.0	610,821.1
	Oxidizer	860,480.4	1,277,960.5	1,694,830.1	2,527,558.0	3,359,516.2
	Stage 1 Total Propellant Mass	**1,016,931.4**	**1,510,316.9**	**2,002,981.0**	**2,987,114.0**	**3,970,337.3**
	Total Rocket Propellant Mass	**1,229,004.5**	**1,825,664.5**	**2,421,491.5**	**3,611,758.8**	**4,800,964.5**
	Total Rocket Inert Mass	**261,090.5**	**386,639.9**	**511,929.8**	**762,085.9**	**1,011,925.9**
	Total Rocket Mass	**1,540,095.0**	**2,287,304.4**	**3,033,421.2**	**4,523,844.7**	**6,012,890.4**

Table B 5: Baseline Parametric Rocket Sizing Model results for the three stage, LOX/LH2 rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	**2,500.0**	**5,000.0**	**10,000.0**	**20,000.0**	**35,000.0**
Stage 3	Fuel Tank	6.2	11.0	21.1	41.9	74.2
	Oxidizer Tank	5.1	8.6	15.2	27.8	46.0
	Fore Inter-Stage Adapter	7.4	11.8	19.9	34.5	54.8
	Inter-Tank Adapter	7.4	11.8	19.9	34.5	54.8
	Thrust Structure	32.0	57.2	109.4	218.3	387.8
	Payload Fairing	500.0	1,000.0	2,000.0	4,000.0	7,000.0
	Fuel Tank Insulation	92.1	130.9	194.0	294.7	417.4
	Oxidizer Tank Insulation	33.3	47.4	70.4	107.2	152.1
	Base Heat Shield	2.2	3.3	5.0	8.0	11.7
	Main Engines	402.0	607.7	1,017.7	1,835.5	3,059.8
	Propellant Feed Lines	0.9	1.6	2.9	5.6	9.6
	Gimbal	118.4	204.1	375.0	715.7	1,225.8
	RCS Engines	79.9	137.7	253.0	483.0	827.2
	RCS Oxidizer Tank	0.1	0.2	0.4	0.7	1.1
	RCS Fuel Tank	0.1	0.2	0.4	0.8	1.3
	Propellant Feed Lines	0.0	0.1	0.1	0.2	0.3
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	110.2	189.9	348.8	665.8	1,140.4
	Main Propellant Reserves	122.4	211.0	387.6	739.8	1,267.1
	Main Propellant Pressurant - He	592.4	1,021.2	1,875.9	3,580.6	6,132.6
	RCS Propellant	204.8	353.1	648.5	1,237.9	2,120.2
	RCS Resuduals	3.7	6.4	11.7	22.3	38.2
	RCS Reserves	4.1	7.1	13.0	24.8	42.4
	RCS Pressurant - He	6.3	10.8	19.9	37.9	65.0
	Stage 2 Total Inert Mass	**3,306.9**	**5,009.0**	**8,385.7**	**15,093.4**	**25,105.7**
	Fuel	941.5	1,623.0	2,981.4	5,690.7	9,746.6
	Oxidizer	5,178.2	8,926.7	16,397.7	31,298.8	53,606.6
	Stage 3 Total Propellant Mass	**6,119.7**	**10,549.8**	**19,379.0**	**36,989.5**	**63,353.2**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**11,926.6**	**20,558.8**	**37,764.7**	**72,082.9**	**123,458.9**
	Fuel Tank	17.9	31.7	60.2	119.1	210.5
	Oxidizer Tank	13.1	21.7	38.3	69.9	115.6
	Fore Inter-Stage Adapter	17.4	27.6	46.3	80.2	126.9
	Inter-Tank Adapter	17.4	27.6	46.3	80.2	126.9
	Thrust Structure	93.0	165.1	314.1	623.8	1,105.4
	Fuel Tank Insulation	175.8	248.8	367.3	556.6	787.2
	Oxidizer Tank Insulation	63.7	90.4	133.7	203.2	288.0
	Base Heat Shield	4.5	6.6	10.2	16.1	23.5
	Main Engines	890.5	1,439.9	2,532.7	4,708.8	7,962.7
	Propellant Feed Lines	2.5	4.3	7.9	15.0	25.7
	Gimbal	322.0	550.9	1,006.2	1,912.9	3,268.7
	Main Propellant Residuals	299.5	512.5	936.1	1,779.5	3,040.8
	Main Propellant Reserves	332.8	569.4	1,040.1	1,977.3	3,378.6
	Main Propellant Pressurant - He	1,610.8	2,756.0	5,033.9	9,569.9	16,352.5
	Stage 2 Total Inert Mass	**3,861.2**	**6,452.5**	**11,573.3**	**21,712.6**	**36,813.1**
	Fuel	2,560.1	4,380.1	8,000.6	15,209.7	25,989.5
	Oxidizer	14,080.6	24,090.6	44,003.1	83,653.5	142,942.0
	Stage 2 Total Propelland Mass	**16,640.7**	**28,470.7**	**52,003.7**	**98,863.2**	**168,931.4**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**32,428.4**	**55,482.0**	**101,341.7**	**192,658.7**	**329,203.5**
	Fuel Tank	51.3	90.4	171.0	337.6	595.8
	Oxidizer Tank	33.2	54.8	96.2	175.4	289.6
	Fore Inter-Stage Adapter	40.7	64.2	107.3	185.8	293.6
	Aft Skirt	40.7	64.2	107.3	185.8	293.6
	Inter-Tank Adapter	40.7	64.2	107.3	185.8	293.6
	Thrust Structure	267.6	473.0	897.1	1,777.1	3,144.6
	Fuel Tank Insulation	333.4	470.7	693.7	1,049.6	1,483.3
	Oxidizer Tank Insulation	121.3	171.6	253.6	384.7	545.0
	Base Heat Shield	9.1	13.4	20.4	32.2	47.1
	Main Engines	2,196.6	3,660.7	6,569.1	12,353.8	20,996.9
	Propellant Feed Lines	6.8	11.6	21.1	40.1	68.3
	Gimbal	866.2	1,476.2	2,688.0	5,098.4	8,699.7
	Main Propellant Residuals	805.8	1,373.3	2,500.6	4,742.8	8,093.0
	Main Propellant Reserves	895.3	1,525.8	2,778.4	5,269.8	8,992.2
	Main Propellant Pressurant - He	4,333.2	7,385.0	13,447.6	25,505.7	43,522.0
	Stage 1 Total Inert Mass	**10,041.9**	**16,899.2**	**30,458.8**	**57,324.6**	**97,358.2**
	Fuel	6,886.9	11,737.2	21,372.5	40,536.9	69,170.5
	Oxidizer	37,878.0	64,554.6	117,549.0	222,952.8	380,438.0
	Stage 1 Total Propellant Mass	**44,764.9**	**76,291.8**	**138,921.5**	**263,489.7**	**449,608.5**
	Total Rocket Propellant Mass	**67,525.2**	**115,312.3**	**210,304.3**	**399,342.3**	**681,893.1**
	Total Rocket Inert Mass	**17,210.0**	**28,360.7**	**50,417.7**	**94,130.6**	**159,277.0**
	Total Rocket Mass	**87,235.2**	**148,673.0**	**270,722.0**	**513,472.9**	**876,170.2**

Table B 6: Baseline Parametric Rocket Sizing Model results for the three stage, LOX/LH2 rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	**50,000.0**	**75,000.0**	**100,000.0**	**150,000.0**	**200,000.0**
Stage 3	Fuel Tank	107.4	163.9	221.6	339.6	460.0
	Oxidizer Tank	63.8	92.7	121.0	176.3	230.5
	Fore Inter-Stage Adapter	73.8	103.8	132.3	186.6	238.4
	Inter-Tank Adapter	73.8	103.8	132.3	186.6	238.4
	Thrust Structure	562.1	860.0	1,164.4	1,787.7	2,425.1
	Payload Fairing	10,000.0	15,000.0	20,000.0	30,000.0	40,000.0
	Fuel Tank Insulation	522.6	676.2	812.4	1,053.4	1,267.2
	Oxidizer Tank Insulation	190.7	247.1	297.3	386.1	465.1
	Base Heat Shield	15.0	19.9	24.3	32.3	39.6
	Main Engines	4,282.7	6,319.0	8,354.1	12,422.0	16,488.1
	Propellant Feed Lines	13.6	20.3	27.0	40.3	53.6
	Gimbal	1,735.4	2,583.9	3,431.8	5,126.8	6,821.0
	RCS Engines	1,171.0	1,743.5	2,315.7	3,459.4	4,602.6
	RCS Oxidizer Tank	1.5	2.2	2.9	4.2	5.5
	RCS Fuel Tank	1.8	2.7	3.5	5.1	6.6
	Propellant Feed Lines	0.5	0.7	0.9	1.3	1.8
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	1,614.4	2,403.7	3,192.5	4,769.2	6,345.3
	Main Propellant Reserves	1,793.7	2,670.7	3,547.2	5,299.2	7,050.3
	Main Propellant Pressurant - He	8,681.6	12,926.4	17,168.4	25,647.8	34,123.4
	RCS Propellant	3,001.5	4,469.0	5,935.6	8,867.2	11,797.4
	RCS Resuduals	54.0	80.4	106.8	159.6	212.4
	RCS Reserves	60.0	89.4	118.7	177.3	235.9
	RCS Pressurant - He	92.0	136.9	181.9	271.7	361.5
	Stage 2 Total Inert Mass	**35,088.9**	**51,692.2**	**68,268.9**	**101,376.0**	**134,445.6**
	Fuel	13,797.9	20,544.2	27,286.2	40,762.7	54,233.2
	Oxidizer	75,888.3	112,993.0	150,074.1	224,194.9	298,282.3
	Stage 3 Total Propellant Mass	**89,686.1**	**133,537.2**	**177,360.3**	**264,957.6**	**352,515.5**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**174,775.0**	**260,229.4**	**345,629.1**	**516,333.6**	**686,961.1**
	Fuel Tank	304.2	463.8	626.7	959.5	1,299.2
	Oxidizer Tank	160.0	232.2	302.8	441.0	576.3
	Fore Inter-Stage Adapter	170.8	240.0	305.9	431.1	550.4
	Inter-Tank Adapter	170.8	240.0	305.9	431.1	550.4
	Thrust Structure	1,600.4	2,445.4	3,309.0	5,076.0	6,882.8
	Fuel Tank Insulation	985.1	1,273.6	1,529.8	1,982.7	2,384.5
	Oxidizer Tank Insulation	360.9	467.4	562.2	729.9	879.0
	Base Heat Shield	30.0	39.8	48.7	64.8	79.3
	Main Engines	11,210.5	16,616.4	22,017.0	32,809.0	43,593.7
	Propellant Feed Lines	36.3	54.0	71.7	107.0	142.3
	Gimbal	4,622.0	6,874.4	9,124.7	13,621.3	18,115.0
	Main Propellant Residuals	4,299.7	6,395.0	8,488.3	12,671.4	16,851.7
	Main Propellant Reserves	4,777.4	7,105.6	9,431.5	14,079.3	18,724.1
	Main Propellant Pressurant - He	23,122.6	34,391.0	45,648.3	68,143.9	90,624.3
	Stage 2 Total Inert Mass	**51,850.5**	**76,838.8**	**101,772.4**	**151,548.1**	**201,253.0**
	Fuel	36,749.2	54,658.4	72,549.9	108,302.6	144,031.3
	Oxidizer	202,120.7	300,621.3	399,024.4	595,664.3	792,172.3
	Stage 2 Total Propelland Mass	**238,869.9**	**355,279.7**	**471,574.3**	**703,966.8**	**936,203.6**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**465,495.5**	**692,347.9**	**918,975.9**	**1,371,848.5**	**1,824,417.7**
	Fuel Tank	860.4	1,311.1	1,770.9	2,709.9	3,668.3
	Oxidizer Tank	400.5	581.0	757.5	1,102.8	1,440.6
	Fore Inter-Stage Adapter	394.8	554.5	706.5	995.4	1,270.5
	Aft Skirt	394.8	554.5	706.5	995.4	1,270.5
	Inter-Tank Adapter	394.8	554.5	706.5	995.4	1,270.5
	Thrust Structure	4,549.1	6,946.3	9,395.5	14,406.2	19,528.8
	Fuel Tank Insulation	1,855.2	2,397.8	2,879.5	3,731.2	4,486.9
	Oxidizer Tank Insulation	682.7	884.0	1,063.0	1,380.0	1,661.9
	Base Heat Shield	60.2	79.8	97.6	129.7	158.8
	Main Engines	29,620.3	43,969.2	58,301.1	86,936.2	115,549.3
	Propellant Feed Lines	96.6	143.5	190.4	284.2	377.8
	Gimbal	12,292.7	18,271.4	24,243.0	36,174.4	48,096.5
	Main Propellant Residuals	11,435.4	16,997.2	22,552.4	33,651.6	44,742.3
	Main Propellant Reserves	12,706.0	18,885.8	25,058.2	37,390.7	49,713.7
	Main Propellant Pressurant - He	61,497.1	91,407.0	121,281.4	180,970.5	240,613.7
	Stage 1 Total Inert Mass	**137,240.6**	**203,537.6**	**269,709.9**	**401,853.7**	**533,850.3**
	Fuel	97,738.7	145,275.3	192,755.3	287,620.6	382,412.8
	Oxidizer	537,562.8	799,014.2	1,060,154.3	1,581,913.4	2,103,270.6
	Stage 1 Total Propellant Mass	**635,301.5**	**944,289.5**	**1,252,909.6**	**1,869,534.0**	**2,485,683.4**
	Total Rocket Propellant Mass	**963,857.6**	**1,433,106.4**	**1,901,844.2**	**2,838,458.5**	**3,774,402.5**
	Total Rocket Inert Mass	**224,180.0**	**332,068.5**	**439,751.2**	**654,777.8**	**869,548.9**
	Total Rocket Mass	**1,238,037.6**	**1,840,175.0**	**2,441,595.4**	**3,643,236.3**	**4,843,951.4**

Table B 7: Light-Weighted Parametric Rocket Sizing Model results for the three stage, LOX/LH2 rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	2,500.0	5,000.0	10,000.0	20,000.0	35,000.0
Stage 3	Fuel Tank	6.0	10.6	20.2	40.1	71.0
	Oxidizer Tank	5.0	8.3	14.6	26.7	44.3
	Fore Inter-Stage Adapter	5.4	8.6	14.4	25.0	39.6
	Inter-Tank Adapter	5.4	8.6	14.4	25.0	39.6
	Thrust Structure	30.9	55.0	104.9	208.9	370.8
	Payload Fairing	375.0	750.0	1,500.0	3,000.0	5,250.0
	Fuel Tank Insulation	90.2	127.9	189.1	287.0	406.2
	Oxidizer Tank Insulation	32.6	46.3	68.6	104.3	148.0
	Base Heat Shield	2.2	3.2	4.9	7.8	11.4
	Main Engines	393.2	590.2	982.9	1,766.3	2,939.1
	Propellant Feed Lines	0.9	1.5	2.8	5.4	9.2
	Gimbal	114.8	196.8	360.5	686.9	1,175.5
	RCS Engines	77.4	132.8	243.2	463.5	793.2
	RCS Oxidizer Tank	0.1	0.2	0.4	0.6	1.1
	RCS Fuel Tank	0.1	0.2	0.4	0.8	1.3
	Propellant Feed Lines	0.0	0.1	0.1	0.2	0.3
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	106.8	183.1	335.3	639.0	1,093.6
	Main Propellant Reserves	118.6	203.5	372.6	710.0	1,215.1
	Main Propellant Pressurant - He	574.1	984.7	1,803.4	3,436.3	5,880.9
	RCS Propellant	198.5	340.4	623.5	1,188.0	2,033.2
	RCS Resuduals	3.6	6.1	11.2	21.4	36.6
	RCS Reserves	4.0	6.8	12.5	23.8	40.7
	RCS Pressurant - He	6.1	10.4	19.1	36.4	62.3
	Stage 2 Total Inert Mass	**3,126.7**	**4,651.4**	**7,675.1**	**13,679.3**	**22,638.9**
	Fuel	912.4	1,565.0	2,866.2	5,461.4	9,346.6
	Oxidizer	5,018.2	8,607.8	15,763.9	30,037.6	51,406.4
	Stage 3 Total Propellant Mass	**5,930.6**	**10,172.8**	**18,630.1**	**35,498.9**	**60,753.1**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**11,557.3**	**19,824.2**	**36,305.1**	**69,178.2**	**118,391.9**
	Fuel Tank	17.3	30.5	57.7	113.9	201.2
	Oxidizer Tank	12.8	21.0	36.9	67.2	111.1
	Fore Inter-Stage Adapter	12.7	20.1	33.5	58.1	91.8
	Inter-Tank Adapter	12.7	20.1	33.5	58.1	91.8
	Thrust Structure	89.9	158.7	301.0	596.8	1,056.6
	Fuel Tank Insulation	172.2	243.0	358.0	541.9	766.0
	Oxidizer Tank Insulation	62.4	88.2	130.3	197.8	280.2
	Base Heat Shield	4.4	6.5	9.9	15.6	22.8
	Main Engines	866.5	1,392.3	2,438.7	4,522.3	7,638.0
	Propellant Feed Lines	2.5	4.2	7.6	14.4	24.6
	Gimbal	312.0	531.1	967.1	1,835.2	3,133.4
	Main Propellant Residuals	290.2	494.0	899.6	1,707.2	2,914.9
	Main Propellant Reserves	322.4	548.9	999.6	1,896.9	3,238.8
	Main Propellant Pressurant - He	1,560.6	2,656.8	4,837.9	9,181.1	15,675.8
	Stage 2 Total Inert Mass	**3,738.7**	**6,215.4**	**11,111.3**	**20,806.6**	**35,247.1**
	Fuel	2,480.4	4,222.5	7,689.0	14,591.8	24,913.9
	Oxidizer	13,642.0	23,223.9	42,289.3	80,254.8	137,026.2
	Stage 2 Total Propelland Mass	**16,122.4**	**27,446.5**	**49,978.3**	**94,846.6**	**161,940.1**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**31,418.4**	**53,486.0**	**97,394.7**	**184,831.4**	**315,579.1**
	Fuel Tank	49.6	86.9	163.8	322.8	569.2
	Oxidizer Tank	32.2	52.9	92.6	168.6	278.2
	Fore Inter-Stage Adapter	29.7	46.7	77.8	134.4	212.3
	Aft Skirt	29.7	46.7	77.8	134.4	212.3
	Inter-Tank Adapter	29.7	46.7	77.8	134.4	212.3
	Thrust Structure	258.6	454.5	859.2	1,699.0	3,004.0
	Fuel Tank Insulation	326.5	459.5	675.8	1,021.4	1,442.7
	Oxidizer Tank Insulation	118.8	167.5	247.0	374.3	530.0
	Base Heat Shield	8.9	13.0	19.9	31.3	45.7
	Main Engines	2,130.5	3,531.0	6,314.0	11,849.7	20,121.3
	Propellant Feed Lines	6.6	11.2	20.3	38.4	65.5
	Gimbal	838.6	1,422.2	2,581.7	4,888.3	8,334.8
	Main Propellant Residuals	780.2	1,323.0	2,401.7	4,547.4	7,753.6
	Main Propellant Reserves	866.8	1,470.0	2,668.6	5,052.7	8,615.1
	Main Propellant Pressurant - He	4,195.5	7,114.8	12,915.8	24,454.8	41,696.8
	Stage 1 Total Inert Mass	**9,701.9**	**16,246.5**	**29,193.6**	**54,851.9**	**93,093.6**
	Fuel	6,668.0	11,307.7	20,527.4	38,866.6	66,269.7
	Oxidizer	36,674.0	62,192.4	112,900.5	213,766.6	364,483.3
	Stage 1 Total Propellant Mass	**43,342.0**	**73,500.1**	**133,427.8**	**252,633.2**	**430,753.0**
	Total Rocket Propellant Mass	**65,394.9**	**111,119.4**	**202,036.2**	**382,978.7**	**653,446.1**
	Total Rocket Inert Mass	**16,567.3**	**27,113.2**	**47,980.0**	**89,337.8**	**150,979.6**
	Total Rocket Mass	**84,462.3**	**143,232.6**	**260,016.2**	**492,316.5**	**839,425.6**

Table B 8: Light-Weighted Parametric Rocket Sizing Model results for the three stage, LOX/LH2 rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	50,000.0	75,000.0	100,000.0	150,000.0	200,000.0
Stage 3	Fuel Tank	102.7	156.7	211.8	324.5	439.6
	Oxidizer Tank	61.3	89.1	116.2	169.4	221.4
	Fore Inter-Stage Adapter	53.4	75.0	95.7	135.0	172.3
	Inter-Tank Adapter	53.4	75.0	95.7	135.0	172.3
	Thrust Structure	537.4	821.8	1,112.7	1,708.0	2,316.8
	Payload Fairing	7,500.0	11,250.0	15,000.0	22,500.0	30,000.0
	Fuel Tank Insulation	508.5	657.8	790.4	1,024.7	1,232.6
	Oxidizer Tank Insulation	185.5	240.4	289.2	375.5	452.3
	Base Heat Shield	14.5	19.3	23.6	31.4	38.4
	Main Engines	4,110.5	6,061.2	8,010.7	11,907.6	15,802.7
	Propellant Feed Lines	13.1	19.5	25.8	38.6	51.3
	Gimbal	1,663.6	2,476.4	3,288.7	4,912.4	6,535.4
	RCS Engines	1,122.6	1,671.0	2,219.2	3,314.8	4,409.9
	RCS Oxidizer Tank	1.5	2.1	2.8	4.1	5.3
	RCS Fuel Tank	1.8	2.6	3.4	4.9	6.4
	Propellant Feed Lines	0.4	0.7	0.9	1.3	1.7
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	1,547.6	2,303.7	3,059.4	4,569.8	6,079.6
	Main Propellant Reserves	1,719.6	2,559.7	3,399.3	5,077.6	6,755.1
	Main Propellant Pressurant - He	8,322.7	12,388.9	16,452.6	24,575.5	32,694.8
	RCS Propellant	2,877.4	4,283.2	5,688.1	8,496.4	11,303.5
	RCS Resuduals	51.8	77.1	102.4	152.9	203.5
	RCS Reserves	57.5	85.7	113.8	169.9	226.1
	RCS Pressurant - He	88.2	131.2	174.3	260.3	346.4
	Stage 2 Total Inert Mass	**31,570.8**	**46,424.1**	**61,252.4**	**90,865.4**	**120,443.5**
	Fuel	13,227.4	19,689.9	26,148.4	39,058.3	51,962.6
	Oxidizer	72,750.6	108,294.6	143,816.3	214,820.9	285,794.2
	Stage 3 Total Propellant Mass	**85,978.0**	**127,984.6**	**169,964.7**	**253,879.2**	**337,756.8**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**167,548.8**	**249,408.7**	**331,217.1**	**494,744.7**	**658,200.4**
	Fuel Tank	290.7	443.2	598.8	916.6	1,241.0
	Oxidizer Tank	153.7	223.0	290.9	423.6	553.5
	Fore Inter-Stage Adapter	123.5	173.5	221.1	311.6	397.8
	Inter-Tank Adapter	123.5	173.5	221.1	311.6	397.8
	Thrust Structure	1,529.2	2,336.1	3,160.6	4,847.9	6,573.0
	Fuel Tank Insulation	958.3	1,238.8	1,487.8	1,928.2	2,318.9
	Oxidizer Tank Insulation	351.0	454.6	546.7	709.7	854.7
	Base Heat Shield	29.2	38.7	47.3	62.8	76.9
	Main Engines	10,748.1	15,924.7	21,096.4	31,431.1	41,759.2
	Propellant Feed Lines	34.8	51.7	68.7	102.5	136.3
	Gimbal	4,429.3	6,586.2	8,741.1	13,047.2	17,350.6
	Main Propellant Residuals	4,120.4	6,126.9	8,131.5	12,137.3	16,140.6
	Main Propellant Reserves	4,578.2	6,807.7	9,035.0	13,485.9	17,934.0
	Main Propellant Pressurant - He	22,158.6	32,949.1	43,729.3	65,271.8	86,800.3
	Stage 2 Total Inert Mass	**49,628.4**	**73,527.8**	**97,376.1**	**144,988.0**	**192,534.7**
	Fuel	35,217.1	52,366.8	69,500.0	103,738.0	137,953.8
	Oxidizer	193,694.1	288,017.6	382,249.8	570,558.9	758,745.8
	Stage 2 Total Propelland Mass	**228,911.2**	**340,384.4**	**451,749.8**	**674,296.9**	**896,699.6**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**446,088.4**	**663,320.9**	**880,343.0**	**1,314,029.6**	**1,747,434.6**
	Fuel Tank	821.8	1,252.1	1,690.9	2,587.3	3,502.2
	Oxidizer Tank	384.6	557.8	727.2	1,058.6	1,382.9
	Fore Inter-Stage Adapter	285.4	400.7	510.5	719.2	918.0
	Aft Skirt	285.4	400.7	510.5	719.2	918.0
	Inter-Tank Adapter	285.4	400.7	510.5	719.2	918.0
	Thrust Structure	4,344.2	6,631.9	8,969.2	13,751.3	18,640.2
	Fuel Tank Insulation	1,804.1	2,331.4	2,799.6	3,627.4	4,362.0
	Oxidizer Tank Insulation	663.8	859.3	1,033.3	1,341.4	1,615.2
	Base Heat Shield	58.4	77.4	94.6	125.8	154.0
	Main Engines	28,374.4	42,108.0	55,825.8	83,235.1	110,624.2
	Propellant Feed Lines	92.5	137.4	182.3	272.1	361.7
	Gimbal	11,773.6	17,495.9	23,211.7	34,632.2	46,044.4
	Main Propellant Residuals	10,952.5	16,275.8	21,592.9	32,217.0	42,833.3
	Main Propellant Reserves	12,169.5	18,084.2	23,992.2	35,796.7	47,592.6
	Main Propellant Pressurant - He	58,900.2	87,527.5	116,121.8	173,255.6	230,347.5
	Stage 1 Total Inert Mass	**131,195.9**	**194,540.9**	**257,773.0**	**384,057.9**	**510,214.1**
	Fuel	93,611.5	139,109.4	184,555.0	275,359.1	366,096.6
	Oxidizer	514,863.0	765,101.9	1,015,052.6	1,514,474.9	2,013,531.2
	Stage 1 Total Propellant Mass	**608,474.5**	**904,211.4**	**1,199,607.6**	**1,789,833.9**	**2,379,627.7**
	Total Rocket Propellant Mass	**923,363.7**	**1,372,580.4**	**1,821,322.1**	**2,718,010.1**	**3,614,084.2**
	Total Rocket Inert Mass	**212,395.1**	**314,492.7**	**416,401.5**	**619,911.4**	**823,192.3**
	Total Rocket Mass	**1,185,758.8**	**1,762,073.1**	**2,337,723.6**	**3,487,921.5**	**4,637,276.4**

Table B 9: Baseline Parametric Rocket Sizing Model results for the two stage, LOX/RP1 rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	2,500.0	5,000.0	10,000.0	20,000.0	35,000.0
Stage 2	Fuel Tank	10.6	17.9	32.0	59.0	98.1
	Oxidizer Tank	16.2	27.4	49.0	90.5	150.4
	Fore Inter-Stage Adapter	9.9	16.1	27.4	47.9	76.2
	Inter-Tank Adapter	9.9	16.1	27.4	47.9	76.2
	Thrust Structure	95.2	173.4	335.9	674.9	1,203.5
	Payload Fairing	500.0	1,000.0	2,000.0	4,000.0	7,000.0
	Oxidizer Tank Insulation	95.2	136.9	204.3	311.9	442.9
	Base Heat Shield	2.8	4.2	6.6	10.5	15.4
	Main Engines	537.2	966.9	1,824.5	3,536.6	6,102.2
	Main Propellant Feed Lines	3.9	6.8	12.6	24.2	41.6
	Gimbal	329.0	576.9	1,071.6	2,059.4	3,539.6
	RCS Engines	222.0	389.3	723.1	1,389.7	2,388.4
	RCS Oxidizer Tank	0.3	0.5	1.0	1.8	3.0
	RCS Fuel Tank	0.4	0.7	1.2	2.2	3.6
	RCS Propellant Feed Lines	0.1	0.2	0.3	0.5	0.9
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	457.4	802.1	1,490.0	2,863.5	4,921.6
	Main Propellant Reserves	508.2	891.3	1,655.6	3,181.7	5,468.4
	Main Propellant Pressurant - He	837.1	1,468.0	2,727.0	5,240.8	9,007.4
	RCS Propellant	569.0	997.8	1,853.5	3,561.9	6,121.9
	RCS Resuduals	10.2	18.0	33.4	64.1	110.2
	RCS Reserves	11.4	20.0	37.1	71.2	122.4
	RCS Pressurant - He	17.4	30.6	56.8	109.1	187.6
	Stage 2 Total Inert Mass	**5,219.4**	**8,536.8**	**15,146.1**	**28,325.4**	**48,057.4**
	Fuel	7,819.0	13,711.6	25,470.8	48,949.4	84,129.9
	Oxidizer	17,592.7	30,851.2	57,309.4	110,136.2	189,292.3
	Stage 2 Total Propellant Mass	**25,411.6**	**44,562.8**	**82,780.2**	**159,085.7**	**273,422.2**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**33,131.0**	**58,099.7**	**107,926.3**	**207,411.1**	**356,479.6**
	Fuel Tank	64.5	109.1	194.9	359.6	597.6
	Oxidizer Tank	98.9	167.4	299.0	551.6	916.6
	Fore Inter-Stage Adapter	51.9	84.0	142.6	249.4	396.5
	Aft Skirt	51.9	84.0	142.6	249.4	396.5
	Inter-Tank Adapter	51.9	84.0	142.6	249.4	396.5
	Thrust Structure	746.8	1,359.1	2,630.7	5,281.4	9,414.4
	Oxidizer Tank Insulation	331.6	476.7	711.5	1,085.7	1,541.7
	Base Heat Shield	11.2	16.7	25.9	41.1	60.4
	Main Engines	3,891.6	6,841.9	12,726.0	24,470.5	42,067.5
	Propellant Feed Lines	26.6	46.6	86.4	166.0	285.2
	Gimbal	2,264.2	3,966.3	7,361.0	14,136.6	24,288.8
	Main Propellant Residuals	3,148.3	5,515.0	10,235.1	19,656.4	33,772.5
	Main Propellant Reserves	3,498.1	6,127.8	11,372.4	21,840.5	37,525.0
	Main Propellant Pressurant - He	5,761.9	10,093.4	18,732.1	35,974.8	61,809.8
	Stage 1 Total Inert Mass	**19,999.4**	**34,971.9**	**64,802.9**	**124,312.4**	**213,469.1**
	Fuel	53,816.5	94,273.3	174,959.6	336,007.0	577,308.3
	Oxidizer	121,087.1	212,115.0	393,659.1	756,015.7	1,298,943.6
	Stage 1 Total Propellant Mass	**174,903.6**	**306,388.3**	**568,618.6**	**1,092,022.6**	**1,876,251.8**
	Total Rocket Propellant Mass	**200,315.2**	**350,951.1**	**651,398.8**	**1,251,108.3**	**2,149,674.0**
	Total Rocket Inert Mass	**25,218.8**	**43,508.7**	**79,949.0**	**152,637.9**	**261,526.6**
	Total Rocket Mass	**228,034.0**	**399,459.8**	**741,347.8**	**1,423,746.2**	**2,446,200.6**

Table B 10: Baseline Parametric Rocket Sizing Model results for the two stage, LOX/RP1 rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	50,000.0	75,000.0	100,000.0	150,000.0	200,000.0
Stage 2	Fuel Tank	136.1	198.0	258.6	377.3	493.5
	Oxidizer Tank	208.7	303.7	396.7	578.6	756.9
	Fore Inter-Stage Adapter	102.7	144.6	184.6	260.6	332.9
	Inter-Tank Adapter	102.7	144.6	184.6	260.6	332.9
	Thrust Structure	1,747.5	2,677.6	3,628.9	5,577.3	7,570.9
	Payload Fairing	10,000.0	15,000.0	20,000.0	30,000.0	40,000.0
	Oxidizer Tank Insulation	555.2	719.2	864.7	1,122.2	1,350.8
	Base Heat Shield	19.7	26.2	32.0	42.7	52.3
	Main Engines	8,666.4	12,938.8	17,210.5	25,753.5	34,296.7
	Main Propellant Feed Lines	58.9	87.9	116.8	174.7	232.6
	Gimbal	5,018.9	7,483.7	9,948.2	14,876.8	19,805.6
	RCS Engines	3,386.6	5,049.9	6,712.8	10,038.6	13,364.4
	RCS Oxidizer Tank	4.1	6.0	7.9	11.5	15.0
	RCS Fuel Tank	5.0	7.3	9.5	13.8	18.1
	RCS Propellant Feed Lines	1.3	2.0	2.6	3.9	5.2
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	6,978.6	10,405.8	13,832.6	20,685.6	27,538.9
	Main Propellant Reserves	7,754.0	11,562.0	15,369.5	22,984.0	30,598.8
	Main Propellant Pressurant - He	12,772.0	19,044.6	25,316.1	37,858.5	50,401.2
	RCS Propellant	8,680.6	12,943.7	17,206.2	25,730.7	34,255.4
	RCS Resuduals	156.3	233.0	309.7	463.2	616.6
	RCS Reserves	173.6	258.9	344.1	514.6	685.1
	RCS Pressurant - He	266.0	396.6	527.2	788.4	1,049.7
	Stage 2 Total Inert Mass	**67,771.1**	**100,610.1**	**133,440.0**	**199,093.0**	**264,749.5**
	Fuel	119,291.8	177,877.7	236,454.3	353,600.7	470,750.6
	Oxidizer	268,406.6	400,224.7	532,022.1	795,601.7	1,059,188.8
	Stage 2 Total Propellant Mass	**387,698.4**	**578,102.4**	**768,476.4**	**1,149,202.4**	**1,529,939.4**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**505,469.5**	**753,712.4**	**1,001,916.3**	**1,498,295.4**	**1,994,688.9**
	Fuel Tank	829.2	1,206.3	1,575.7	2,298.8	3,007.2
	Oxidizer Tank	1,271.8	1,850.2	2,416.7	3,525.9	4,612.5
	Fore Inter-Stage Adapter	534.8	753.1	961.1	1,356.8	1,734.0
	Aft Skirt	534.8	753.1	961.1	1,356.8	1,734.0
	Inter-Tank Adapter	534.8	753.1	961.1	1,356.8	1,734.0
	Thrust Structure	13,668.3	20,941.6	28,383.1	43,628.3	59,232.9
	Oxidizer Tank Insulation	1,932.9	2,503.9	3,011.2	3,908.8	4,705.8
	Base Heat Shield	77.5	102.9	126.0	167.7	205.6
	Main Engines	59,656.9	88,968.7	118,282.0	176,921.3	235,580.7
	Propellant Feed Lines	404.3	602.9	801.5	1,198.7	1,596.1
	Gimbal	34,436.5	51,347.2	68,258.7	102,089.1	135,931.0
	Main Propellant Residuals	47,882.5	71,396.1	94,910.9	141,950.6	189,006.4
	Main Propellant Reserves	53,202.8	79,329.0	105,456.5	157,722.9	210,007.1
	Main Propellant Pressurant - He	87,633.6	130,667.8	173,704.0	259,795.2	345,915.8
	Stage 1 Total Inert Mass	**302,600.8**	**451,175.8**	**599,809.5**	**897,277.8**	**1,195,003.1**
	Fuel	818,504.5	1,220,446.5	1,622,408.2	2,426,506.3	3,230,879.2
	Oxidizer	1,841,635.2	2,746,004.6	3,650,418.5	5,459,639.1	7,269,478.2
	Stage 1 Total Propellant Mass	**2,660,139.8**	**3,966,451.1**	**5,272,826.8**	**7,886,145.4**	**10,500,357.4**
	Total Rocket Propellant Mass	**3,047,838.2**	**4,544,553.5**	**6,041,303.1**	**9,035,347.8**	**12,030,296.8**
	Total Rocket Inert Mass	**370,371.8**	**551,785.9**	**733,249.5**	**1,096,370.9**	**1,459,752.6**
	Total Rocket Mass	**3,468,210.0**	**5,171,339.4**	**6,874,552.6**	**10,281,718.7**	**13,690,049.4**

Table B 11: Light-Weighted Parametric Rocket Sizing Model results for the two stage, LOX/RP1 rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	**2,500.0**	**5,000.0**	**10,000.0**	**20,000.0**	**35,000.0**
Stage 2	Fuel Tank	10.2	17.3	30.8	56.7	94.2
	Oxidizer Tank	15.7	26.5	47.2	87.0	144.6
	Fore Inter-Stage Adapter	7.3	11.7	19.8	34.7	55.1
	Inter-Tank Adapter	7.3	11.7	19.8	34.7	55.1
	Thrust Structure	91.9	166.6	321.8	645.5	1,150.3
	Payload Fairing	375.0	750.0	1,500.0	3,000.0	5,250.0
	Oxidizer Tank Insulation	93.1	133.6	199.1	303.6	430.9
	Base Heat Shield	2.8	4.1	6.4	10.2	14.9
	Main Engines	518.6	930.0	1,751.2	3,390.7	5,847.6
	Main Propellant Feed Lines	3.7	6.5	12.1	23.2	39.8
	Gimbal	318.2	555.6	1,029.3	1,975.3	3,392.7
	RCS Engines	214.7	374.9	694.6	1,332.9	2,289.3
	RCS Oxidizer Tank	0.3	0.5	0.9	1.7	2.9
	RCS Fuel Tank	0.4	0.6	1.1	2.1	3.5
	RCS Propellant Feed Lines	0.1	0.1	0.3	0.5	0.9
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	442.5	772.5	1,431.2	2,746.5	4,717.4
	Main Propellant Reserves	491.6	858.4	1,590.3	3,051.7	5,241.5
	Main Propellant Pressurant - He	809.8	1,413.9	2,619.4	5,026.6	8,633.6
	RCS Propellant	550.4	961.0	1,780.3	3,416.4	5,867.9
	RCS Resuduals	9.9	17.3	32.0	61.5	105.6
	RCS Reserves	11.0	19.2	35.6	68.3	117.4
	RCS Pressurant - He	16.9	29.4	54.6	104.7	179.8
	Stage 2 Total Inert Mass	**4,967.3**	**8,037.4**	**14,153.9**	**26,350.3**	**44,610.9**
	Fuel	7,563.7	13,205.8	24,465.8	46,948.8	80,638.9
	Oxidizer	17,018.4	29,713.0	55,048.0	105,634.9	181,437.5
	Stage 2 Total Propellant Mass	**24,582.2**	**42,918.8**	**79,513.8**	**152,583.7**	**262,076.4**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**32,049.5**	**55,956.2**	**103,667.7**	**198,934.0**	**341,687.3**
	Fuel Tank	62.4	105.2	187.6	345.5	573.8
	Oxidizer Tank	95.8	161.4	287.7	530.0	880.2
	Fore Inter-Stage Adapter	37.8	60.9	103.2	180.4	286.6
	Aft Skirt	37.8	60.9	103.2	180.4	286.6
	Inter-Tank Adapter	37.8	60.9	103.2	180.4	286.6
	Thrust Structure	720.0	1,304.2	2,517.4	5,046.5	8,989.9
	Oxidizer Tank Insulation	324.4	465.0	692.8	1,056.2	1,499.1
	Base Heat Shield	10.9	16.2	25.1	39.9	58.6
	Main Engines	3,759.3	6,581.5	12,211.0	23,448.5	40,287.4
	Propellant Feed Lines	25.7	44.8	82.9	159.1	273.1
	Gimbal	2,187.9	3,816.1	7,063.9	13,547.0	23,261.8
	Main Propellant Residuals	3,042.1	5,306.1	9,822.0	18,836.6	32,344.6
	Main Propellant Reserves	3,380.1	5,895.7	10,913.3	20,929.5	35,938.4
	Main Propellant Pressurant - He	5,567.6	9,711.1	17,976.0	34,474.4	59,196.4
	Stage 1 Total Inert Mass	**19,289.6**	**33,590.1**	**62,089.4**	**118,954.2**	**204,163.3**
	Fuel	52,002.0	90,702.6	167,897.5	321,993.0	552,898.9
	Oxidizer	117,004.5	204,080.9	377,769.3	724,484.2	1,244,022.6
	Stage 1 Total Propellant Mass	**169,006.5**	**294,783.5**	**545,666.8**	**1,046,477.1**	**1,796,921.5**
	Total Rocket Propellant Mass	**193,588.7**	**337,702.3**	**625,180.6**	**1,199,060.8**	**2,058,997.9**
	Total Rocket Inert Mass	**24,256.9**	**41,627.6**	**76,243.3**	**145,304.5**	**248,774.2**
	Total Rocket Mass	**220,345.6**	**384,329.8**	**711,423.9**	**1,364,365.3**	**2,342,772.1**

Table B 12: Light-Weighted Parametric Rocket Sizing Model results for the two stage, LOX/RP1 rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	50,000.0	75,000.0	100,000.0	150,000.0	200,000.0
Stage 2	Fuel Tank	130.8	190.2	248.4	362.3	473.9
	Oxidizer Tank	200.6	291.7	381.0	555.7	726.9
	Fore Inter-Stage Adapter	74.3	104.6	133.4	188.3	240.7
	Inter-Tank Adapter	74.3	104.6	133.4	188.3	240.7
	Thrust Structure	1,669.7	2,557.8	3,466.2	5,326.8	7,230.7
	Payload Fairing	7,500.0	11,250.0	15,000.0	22,500.0	30,000.0
	Oxidizer Tank Insulation	540.1	699.5	841.0	1,091.4	1,313.6
	Base Heat Shield	19.1	25.4	31.1	41.4	50.7
	Main Engines	8,303.3	12,394.9	16,485.9	24,667.8	32,850.0
	Main Propellant Feed Lines	56.5	84.2	111.9	167.3	222.8
	Gimbal	4,809.4	7,169.9	9,530.2	14,250.5	18,971.0
	RCS Engines	3,245.3	4,838.1	6,430.8	9,615.9	12,801.2
	RCS Oxidizer Tank	4.0	5.8	7.6	11.0	14.4
	RCS Fuel Tank	4.8	7.0	9.1	13.3	17.4
	RCS Propellant Feed Lines	1.3	1.9	2.5	3.7	5.0
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	6,687.3	9,969.5	13,251.3	19,814.7	26,378.3
	Main Propellant Reserves	7,430.3	11,077.2	14,723.7	22,016.3	29,309.3
	Main Propellant Pressurant - He	12,238.9	18,246.0	24,252.3	36,264.4	48,277.1
	RCS Propellant	8,318.2	12,401.0	16,483.2	24,647.3	32,811.8
	RCS Resuduals	149.7	223.2	296.7	443.7	590.6
	RCS Reserves	166.4	248.0	329.7	492.9	656.2
	RCS Pressurant - He	254.9	380.0	505.1	755.3	1,005.4
	Stage 2 Total Inert Mass	**62,854.9**	**93,246.5**	**123,630.5**	**184,394.4**	**245,163.6**
	Fuel	114,312.2	170,419.0	226,518.1	338,712.3	450,911.8
	Oxidizer	257,202.4	383,442.7	509,665.8	762,102.6	1,014,551.6
	Stage 2 Total Propellant Mass	**371,514.6**	**553,861.7**	**736,183.9**	**1,100,814.9**	**1,465,463.4**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**484,369.5**	**722,108.2**	**959,814.4**	**1,435,209.2**	**1,910,627.0**
	Fuel Tank	796.1	1,157.9	1,512.4	2,206.4	2,886.3
	Oxidizer Tank	1,221.0	1,776.0	2,319.7	3,384.2	4,427.0
	Fore Inter-Stage Adapter	386.4	544.1	694.3	980.2	1,252.7
	Aft Skirt	386.4	544.1	694.3	980.2	1,252.7
	Inter-Tank Adapter	386.4	544.1	694.3	980.2	1,252.7
	Thrust Structure	13,048.8	19,989.0	27,089.9	41,638.1	56,529.7
	Oxidizer Tank Insulation	1,879.3	2,434.2	2,927.2	3,799.6	4,574.2
	Base Heat Shield	75.1	99.8	122.1	162.6	199.3
	Main Engines	57,120.1	85,172.4	113,227.3	169,351.8	225,497.8
	Propellant Feed Lines	387.2	577.2	767.2	1,147.4	1,527.8
	Gimbal	32,973.0	49,157.0	65,342.5	97,722.0	130,113.9
	Main Propellant Residuals	45,847.5	68,350.7	90,856.1	135,878.4	180,918.1
	Main Propellant Reserves	50,941.7	75,945.3	100,951.2	150,976.0	201,020.1
	Main Propellant Pressurant - He	83,909.3	125,094.2	166,283.0	248,682.0	331,112.7
	Stage 1 Total Inert Mass	**289,358.5**	**431,386.0**	**573,481.7**	**857,889.2**	**1,142,564.9**
	Fuel	783,718.8	1,168,388.8	1,553,094.9	2,322,708.2	3,092,616.4
	Oxidizer	1,763,367.2	2,628,874.9	3,494,463.5	5,226,093.5	6,958,387.0
	Stage 1 Total Propellant Mass	**2,547,086.0**	**3,797,263.7**	**5,047,558.4**	**7,548,801.8**	**10,051,003.4**
	Total Rocket Propellant Mass	**2,918,600.6**	**4,351,125.4**	**5,783,742.3**	**8,649,616.6**	**11,516,466.8**
	Total Rocket Inert Mass	**352,213.4**	**524,632.5**	**697,112.1**	**1,042,283.6**	**1,387,728.5**
	Total Rocket Mass	**3,320,813.9**	**4,950,757.9**	**6,580,854.4**	**9,841,900.2**	**13,104,195.2**

Table B 13: Baseline Parametric Rocket Sizing Model results for the three stage, LOX/RP1 rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	**2,500.0**	**5,000.0**	**10,000.0**	**20,000.0**	**35,000.0**
Stage 3	Fuel Tank	3.9	6.7	12.0	22.2	36.9
	Oxidizer Tank	6.1	10.3	18.4	34.0	56.6
	Fore Inter-Stage Adapter	4.1	6.6	11.2	19.6	31.2
	Inter-Tank Adapter	4.1	6.6	11.2	19.6	31.2
	Thrust Structure	38.9	71.1	138.0	277.6	495.4
	Payload Fairing	500.0	1,000.0	2,000.0	4,000.0	7,000.0
	Oxidizer Tank Insulation	48.3	69.6	104.0	158.8	225.6
	Base Heat Shield	1.3	2.0	3.1	5.0	7.3
	Main Engines	213.9	400.9	774.4	1,520.6	2,639.4
	Propellant Feed Lines	1.4	2.4	4.4	8.5	14.7
	Gimbal	142.5	250.3	465.8	896.3	1,541.8
	RCS Engines	96.1	168.9	314.3	604.8	1,040.4
	RCS Oxidizer Tank	0.1	0.2	0.4	0.8	1.4
	RCS Fuel Tank	0.2	0.3	0.5	1.0	1.6
	Propellant Feed Lines	0.0	0.1	0.1	0.2	0.4
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	160.5	282.0	524.7	1,009.7	1,736.7
	Main Propellant Reserves	178.3	313.3	583.0	1,121.8	1,929.6
	Main Propellant Pressurant - He	293.7	516.1	960.3	1,847.9	3,178.4
	RCS Propellant	246.4	433.0	805.6	1,550.3	2,666.6
	RCS Resuduals	4.4	7.8	14.5	27.9	48.0
	RCS Reserves	4.9	8.7	16.1	31.0	53.3
	RCS Pressurant - He	7.6	13.3	24.7	47.5	81.7
	Stage 3 Total Inert Mass	**2,932.7**	**4,545.9**	**7,762.7**	**14,181.3**	**23,794.3**
	Fuel	2,743.1	4,820.0	8,968.9	17,259.1	29,686.9
	Oxidizer	6,172.0	10,845.0	20,180.0	38,832.9	66,795.5
	Stage 3 Total Propellant Mass	**8,915.0**	**15,665.0**	**29,148.9**	**56,092.0**	**96,482.4**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**14,347.8**	**25,210.9**	**46,911.6**	**90,273.3**	**155,276.7**
	Fuel Tank	12.2	20.6	36.9	68.2	113.5
	Oxidizer Tank	18.7	31.6	56.7	104.7	174.1
	Fore Inter-Stage Adapter	11.3	18.3	31.2	54.7	87.0
	Inter-Tank Adapter	11.3	18.3	31.2	54.7	87.0
	Thrust Structure	140.0	255.6	495.9	997.3	1,779.4
	Oxidizer Tank Insulation	104.9	151.1	225.8	344.8	489.8
	Base Heat Shield	3.2	4.7	7.3	11.7	17.2
	Main Engines	785.5	1,405.0	2,641.8	5,112.1	8,814.6
	Propellant Feed Lines	4.5	7.9	14.7	28.2	48.6
	Gimbal	472.2	829.6	1,543.2	2,968.4	5,104.4
	Main Propellant Residuals	531.9	934.5	1,738.2	3,343.6	5,749.7
	Main Propellant Reserves	591.0	1,038.3	1,931.4	3,715.1	6,388.6
	Main Propellant Pressurant - He	973.5	1,710.3	3,181.3	6,119.4	10,523.0
	Stage 2 Total Inert Mass	**3,660.2**	**6,426.0**	**11,935.6**	**22,923.0**	**39,376.8**
	Fuel	9,092.7	15,974.3	29,713.6	57,155.9	98,285.9
	Oxidizer	20,458.6	35,942.2	66,855.6	128,600.8	221,143.4
	Stage 2 Propellant Mass	**29,551.4**	**51,916.6**	**96,569.2**	**185,756.7**	**319,429.3**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**47,559.4**	**83,553.5**	**155,416.4**	**298,952.9**	**514,082.9**
	Fuel Tank	37.4	63.5	113.6	209.9	349.0
	Oxidizer Tank	57.4	97.4	174.3	321.9	535.3
	Fore Inter-Stage Adapter	31.6	51.2	87.1	152.5	242.7
	Aft Skirt	31.6	51.2	87.1	152.5	242.7
	Inter-Tank Adapter	31.6	51.2	87.1	152.5	242.7
	Thrust Structure	503.6	918.9	1,782.1	3,583.0	6,391.8
	Oxidizer Tank Insulation	227.9	328.1	490.2	748.7	1,063.5
	Base Heat Shield	7.4	11.1	17.2	27.4	40.2
	Main Engines	2,680.5	4,732.3	8,827.6	17,006.3	29,264.3
	Propellant Feed Lines	14.9	26.2	48.6	93.5	160.8
	Gimbal	1,565.5	2,749.2	5,111.9	9,830.4	16,902.3
	Main Propellant Residuals	1,763.4	3,096.8	5,758.1	11,073.1	19,039.1
	Main Propellant Reserves	1,959.3	3,440.8	6,397.9	12,303.5	21,154.5
	Main Propellant Pressurant - He	3,227.3	5,667.6	10,538.4	20,265.8	34,845.0
	Stage 1 Total Inert Mass	**12,139.5**	**21,285.4**	**39,521.4**	**75,921.0**	**130,473.9**
	Fuel	30,143.6	52,936.0	98,429.5	189,284.2	325,454.5
	Oxidizer	67,823.1	119,106.0	221,466.3	425,889.5	732,272.7
	Stage 1 Total Propellant Mass	**97,966.7**	**172,042.1**	**319,895.8**	**615,173.7**	**1,057,727.2**
	Total Rocket Propellant Mass	**136,433.2**	**239,623.6**	**445,613.8**	**857,022.3**	**1,473,638.9**
	Total Rocket Inert Mass	**18,732.4**	**32,257.3**	**59,219.7**	**113,025.3**	**193,645.0**
	Total Rocket Mass	**157,665.6**	**276,880.9**	**514,833.5**	**990,047.6**	**1,702,283.9**

Table B 14: Baseline Parametric Rocket Sizing Model results for the three stage, LOX/RP1 rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	**50,000.0**	**75,000.0**	**100,000.0**	**150,000.0**	**200,000.0**
Stage 3	Fuel Tank	51.2	74.6	97.4	142.1	185.9
	Oxidizer Tank	78.6	114.4	149.4	218.0	285.1
	Fore Inter-Stage Adapter	42.1	59.3	75.7	106.8	136.5
	Inter-Tank Adapter	42.1	59.3	75.7	106.8	136.5
	Thrust Structure	719.7	1,103.1	1,495.3	2,298.5	3,120.4
	Payload Fairing	10,000.0	15,000.0	20,000.0	30,000.0	40,000.0
	Oxidizer Tank Insulation	282.9	366.5	440.8	572.0	688.5
	Base Heat Shield	9.4	12.5	15.3	20.4	25.0
	Main Engines	3,757.8	5,621.4	7,484.8	11,211.3	14,937.7
	Propellant Feed Lines	20.8	31.0	41.3	61.7	82.2
	Gimbal	2,187.0	3,262.2	4,337.2	6,487.1	8,637.0
	RCS Engines	1,475.7	2,201.2	2,926.7	4,377.4	5,828.0
	RCS Oxidizer Tank	1.9	2.8	3.6	5.3	6.9
	RCS Fuel Tank	2.3	3.3	4.3	6.3	8.3
	Propellant Feed Lines	0.6	0.9	1.1	1.7	2.3
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	2,463.5	3,674.6	4,885.5	7,307.2	9,728.8
	Main Propellant Reserves	2,737.2	4,082.9	5,428.4	8,119.1	10,809.8
	Main Propellant Pressurant - He	4,508.6	6,725.1	8,941.4	13,373.5	17,805.5
	RCS Propellant	3,782.6	5,642.2	7,501.5	11,220.0	14,938.3
	RCS Resuduals	68.1	101.6	135.0	202.0	268.9
	RCS Reserves	75.7	112.8	150.0	224.4	298.8
	RCS Pressurant - He	115.9	172.9	229.9	343.8	457.7
	Stage 3 Total Inert Mass	**33,399.6**	**49,400.4**	**65,396.2**	**97,381.5**	**129,364.2**
	Fuel	42,110.8	62,813.2	83,513.1	124,909.8	166,305.1
	Oxidizer	94,749.2	141,329.7	187,904.5	281,047.0	374,186.4
	Stage 3 Total Propellant Mass	**136,860.0**	**204,142.9**	**271,417.6**	**405,956.7**	**540,491.5**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**220,259.6**	**328,543.3**	**436,813.7**	**653,338.2**	**869,855.6**
	Fuel Tank	157.5	229.2	299.4	436.8	571.4
	Oxidizer Tank	241.6	351.6	459.3	670.0	876.5
	Fore Inter-Stage Adapter	117.4	165.3	211.0	297.9	380.7
	Inter-Tank Adapter	117.4	165.3	211.0	297.9	380.7
	Thrust Structure	2,584.4	3,960.7	5,368.7	8,252.5	11,203.4
	Oxidizer Tank Insulation	614.2	795.6	956.8	1,241.8	1,494.8
	Base Heat Shield	22.0	29.2	35.8	47.7	58.4
	Main Engines	12,515.7	18,682.9	24,849.4	37,182.3	49,515.9
	Propellant Feed Lines	68.9	102.7	136.5	204.2	271.9
	Gimbal	7,239.7	10,797.6	14,355.3	21,470.4	28,585.9
	Main Propellant Residuals	8,154.9	12,162.7	16,170.1	24,184.7	32,199.8
	Main Propellant Reserves	9,061.0	13,514.1	17,966.7	26,871.9	35,777.5
	Main Propellant Pressurant - He	14,924.9	22,259.9	29,594.1	44,262.4	58,931.4
	Stage 2 Total Inert Mass	**55,819.5**	**83,216.9**	**110,614.1**	**165,420.6**	**220,248.3**
	Fuel	139,400.0	207,909.1	276,411.5	413,413.9	550,423.6
	Oxidizer	313,649.9	467,795.4	621,925.8	930,181.3	1,238,453.1
	Stage 2 Propellant Mass	**453,049.9**	**675,704.5**	**898,337.2**	**1,343,595.3**	**1,788,876.6**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**729,129.0**	**1,087,464.7**	**1,445,765.1**	**2,162,354.0**	**2,878,980.5**
	Fuel Tank	484.4	704.9	920.9	1,343.6	1,757.7
	Oxidizer Tank	743.0	1,081.2	1,412.4	2,060.8	2,695.9
	Fore Inter-Stage Adapter	327.4	461.1	588.5	830.9	1,062.0
	Aft Skirt	327.4	461.1	588.5	830.9	1,062.0
	Inter-Tank Adapter	327.4	461.1	588.5	830.9	1,062.0
	Thrust Structure	9,283.2	14,227.1	19,285.1	29,646.5	40,250.8
	Oxidizer Tank Insulation	1,333.7	1,727.9	2,078.0	2,697.5	3,247.4
	Base Heat Shield	51.6	68.5	83.9	111.7	136.9
	Main Engines	41,518.2	61,938.9	82,359.8	123,206.7	164,062.0
	Propellant Feed Lines	228.0	340.1	452.1	676.3	900.5
	Gimbal	23,971.8	35,753.0	47,534.3	71,099.8	94,670.2
	Main Propellant Residuals	27,002.4	40,273.0	53,543.7	80,088.3	106,638.5
	Main Propellant Reserves	30,002.7	44,747.8	59,493.0	88,987.0	118,487.2
	Main Propellant Pressurant - He	49,419.2	73,706.8	97,994.6	146,576.1	195,167.7
	Stage 1 Total Inert Mass	**185,020.4**	**275,952.5**	**366,923.5**	**548,987.1**	**731,200.6**
	Fuel	461,579.3	688,427.0	915,276.5	1,369,031.1	1,822,880.2
	Oxidizer	1,038,553.3	1,548,960.8	2,059,372.2	3,080,319.9	4,101,480.5
	Stage 1 Total Propellant Mass	**1,500,132.6**	**2,237,387.8**	**2,974,648.8**	**4,449,351.0**	**5,924,360.7**
	Total Rocket Propellant Mass	**2,090,042.5**	**3,117,235.2**	**4,144,403.5**	**6,198,902.9**	**8,253,728.8**
	Total Rocket Inert Mass	**274,239.5**	**408,569.8**	**542,933.7**	**811,789.1**	**1,080,813.0**
	Total Rocket Mass	**2,414,281.9**	**3,600,804.9**	**4,787,337.3**	**7,160,692.0**	**9,534,541.8**

Table B 15: Light-Weighted Parametric Rocket Sizing Model results for the three stage, LOX/RP1 rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	2,500.0	5,000.0	10,000.0	20,000.0	35,000.0
Stage 3	Fuel Tank	3.8	6.5	11.6	21.3	35.5
	Oxidizer Tank	5.9	9.9	17.7	32.7	54.4
	Fore Inter-Stage Adapter	3.0	4.8	8.1	14.2	22.6
	Inter-Tank Adapter	3.0	4.8	8.1	14.2	22.6
	Thrust Structure	37.6	68.3	132.2	265.6	473.7
	Payload Fairing	375.0	750.0	1,500.0	3,000.0	5,250.0
	Oxidizer Tank Insulation	47.3	67.9	101.4	154.7	219.6
	Base Heat Shield	1.3	2.0	3.0	4.8	7.1
	Main Engines	206.0	385.1	742.9	1,457.9	2,529.7
	Propellant Feed Lines	1.3	2.3	4.3	8.2	14.1
	Gimbal	137.9	241.2	447.7	860.1	1,478.5
	RCS Engines	93.0	162.8	302.1	580.4	997.7
	RCS Oxidizer Tank	0.1	0.2	0.4	0.8	1.3
	RCS Fuel Tank	0.2	0.3	0.5	1.0	1.6
	Propellant Feed Lines	0.0	0.1	0.1	0.2	0.4
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	155.3	271.7	504.2	968.9	1,665.4
	Main Propellant Reserves	172.6	301.9	560.3	1,076.5	1,850.4
	Main Propellant Pressurant - He	284.3	497.3	922.9	1,773.2	3,048.0
	RCS Propellant	238.5	417.2	774.2	1,487.7	2,557.2
	RCS Resuduals	4.3	7.5	13.9	26.8	46.0
	RCS Reserves	4.8	8.3	15.5	29.8	51.1
	RCS Pressurant - He	7.3	12.8	23.7	45.6	78.4
	Stage 3 Total Inert Mass	**2,758.5**	**4,199.0**	**7,070.9**	**12,800.6**	**21,381.3**
	Fuel	2,655.2	4,644.8	8,619.6	16,561.9	28,468.5
	Oxidizer	5,974.1	10,450.8	19,394.0	37,264.3	64,054.0
	Stage 3 Total Propellant Mass	**8,629.3**	**15,095.6**	**28,013.6**	**53,826.2**	**92,522.5**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**13,887.8**	**24,294.6**	**45,084.5**	**86,626.7**	**148,903.7**
	Fuel Tank	11.8	19.9	35.6	65.6	109.1
	Oxidizer Tank	18.1	30.6	54.6	100.7	167.3
	Fore Inter-Stage Adapter	8.3	13.3	22.6	39.6	62.9
	Inter-Tank Adapter	8.3	13.3	22.6	39.6	62.9
	Thrust Structure	135.2	245.6	475.1	954.0	1,701.0
	Oxidizer Tank Insulation	102.7	147.5	220.0	335.7	476.6
	Base Heat Shield	3.1	4.6	7.1	11.3	16.7
	Main Engines	758.9	1,352.2	2,536.8	4,902.9	8,449.3
	Propellant Feed Lines	4.3	7.6	14.1	27.1	46.5
	Gimbal	456.9	799.2	1,482.6	2,847.7	4,893.6
	Main Propellant Residuals	514.7	900.2	1,670.0	3,207.7	5,512.3
	Main Propellant Reserves	571.9	1,000.2	1,855.6	3,564.1	6,124.8
	Main Propellant Pressurant - He	941.9	1,647.6	3,056.4	5,870.6	10,088.5
	Stage 2 Total Inert Mass	**3,536.0**	**6,181.8**	**11,453.2**	**21,966.5**	**37,711.5**
	Fuel	8,797.8	15,388.4	28,547.4	54,831.7	94,227.2
	Oxidizer	19,794.9	34,623.9	64,231.7	123,371.4	212,011.2
	Stage 2 Propellant Mass	**28,592.7**	**50,012.3**	**92,779.2**	**178,203.1**	**306,238.4**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**46,016.5**	**80,488.7**	**149,316.8**	**286,796.3**	**492,853.6**
	Fuel Tank	36.3	61.3	109.4	201.8	335.4
	Oxidizer Tank	55.6	94.0	167.8	309.5	514.4
	Fore Inter-Stage Adapter	23.0	37.2	63.1	110.4	175.5
	Aft Skirt	23.0	37.2	63.1	110.4	175.5
	Inter-Tank Adapter	23.0	37.2	63.1	110.4	175.5
	Thrust Structure	485.9	882.5	1,706.8	3,426.2	6,108.0
	Oxidizer Tank Insulation	223.0	320.2	477.6	728.7	1,034.6
	Base Heat Shield	7.2	10.8	16.7	26.6	39.0
	Main Engines	2,591.2	4,555.5	8,476.4	16,307.3	28,044.6
	Propellant Feed Lines	14.4	25.2	46.7	89.7	154.1
	Gimbal	1,514.0	2,647.2	4,909.3	9,427.1	16,198.6
	Main Propellant Residuals	1,705.4	2,981.9	5,529.9	10,618.9	18,246.5
	Main Propellant Reserves	1,894.9	3,313.2	6,144.3	11,798.8	20,273.9
	Main Propellant Pressurant - He	3,121.2	5,457.4	10,120.7	19,434.5	33,394.4
	Stage 1 Total Inert Mass	**11,718.2**	**20,460.5**	**37,895.0**	**72,700.2**	**124,870.0**
	Fuel	29,151.8	50,972.1	94,528.4	181,519.7	311,905.7
	Oxidizer	65,591.6	114,687.1	212,689.0	408,419.3	701,787.9
	Stage 1 Total Propellant Mass	**94,743.4**	**165,659.2**	**307,217.4**	**589,939.0**	**1,013,693.6**
	Total Rocket Propellant Mass	**131,965.4**	**230,767.1**	**428,010.1**	**821,968.3**	**1,412,454.5**
	Total Rocket Inert Mass	**18,012.7**	**30,841.3**	**56,419.1**	**107,467.2**	**183,962.8**
	Total Rocket Mass	**152,478.1**	**266,608.4**	**494,429.2**	**949,435.4**	**1,631,417.3**

Table B 16: Light-Weighted Parametric Rocket Sizing Model results for the three stage, LOX/RP1 rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	50,000.0	75,000.0	100,000.0	150,000.0	200,000.0
Stage 3	Fuel Tank	49.2	71.6	93.6	136.5	178.6
	Oxidizer Tank	75.5	109.9	143.5	209.4	273.9
	Fore Inter-Stage Adapter	30.4	42.9	54.7	77.3	98.7
	Inter-Tank Adapter	30.4	42.9	54.7	77.3	98.7
	Thrust Structure	688.0	1,054.2	1,428.9	2,196.3	2,981.4
	Payload Fairing	7,500.0	11,250.0	15,000.0	22,500.0	30,000.0
	Oxidizer Tank Insulation	275.3	356.6	428.8	556.5	669.8
	Base Heat Shield	9.1	12.1	14.8	19.8	24.2
	Main Engines	3,601.2	5,386.7	7,172.0	10,742.3	14,312.5
	Propellant Feed Lines	19.9	29.7	39.5	59.1	78.7
	Gimbal	2,096.7	3,126.8	4,156.7	6,216.5	8,276.3
	RCS Engines	1,414.8	2,109.9	2,804.9	4,194.8	5,584.7
	RCS Oxidizer Tank	1.8	2.7	3.5	5.1	6.6
	RCS Fuel Tank	2.2	3.2	4.2	6.1	8.0
	Propellant Feed Lines	0.6	0.8	1.1	1.6	2.2
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	2,361.7	3,522.0	4,682.2	7,002.4	9,322.6
	Main Propellant Reserves	2,624.1	3,913.4	5,202.5	7,780.5	10,358.4
	Main Propellant Pressurant - He	4,322.4	6,446.0	8,569.3	12,815.7	17,062.0
	RCS Propellant	3,626.3	5,408.0	7,189.4	10,752.0	14,314.5
	RCS Resuduals	65.3	97.3	129.4	193.5	257.7
	RCS Reserves	72.5	108.2	143.8	215.0	286.3
	RCS Pressurant - He	111.1	165.7	220.3	329.5	438.6
	Stage 3 Total Inert Mass	**29,954.8**	**44,236.6**	**58,513.9**	**87,063.2**	**115,610.5**
	Fuel	40,371.4	60,205.8	80,038.1	119,699.8	159,360.5
	Oxidizer	90,835.6	135,463.2	180,085.6	269,324.5	358,561.0
	Stage 3 Total Propellant Mass	**131,206.9**	**195,669.0**	**260,123.7**	**389,024.2**	**517,921.5**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**211,161.7**	**314,905.6**	**418,637.6**	**626,087.4**	**833,532.0**
	Fuel Tank	151.4	220.2	287.6	419.6	548.9
	Oxidizer Tank	232.2	337.8	441.2	643.6	841.9
	Fore Inter-Stage Adapter	84.9	119.5	152.6	215.4	275.2
	Inter-Tank Adapter	84.9	119.5	152.6	215.4	275.2
	Thrust Structure	2,469.9	3,784.4	5,129.1	7,883.5	10,701.9
	Oxidizer Tank Insulation	597.5	773.9	930.6	1,207.8	1,453.8
	Base Heat Shield	21.4	28.4	34.7	46.2	56.7
	Main Engines	11,994.3	17,901.6	23,808.4	35,621.9	47,436.3
	Propellant Feed Lines	66.0	98.4	130.8	195.7	260.5
	Gimbal	6,938.9	10,346.9	13,754.7	20,570.2	27,386.1
	Main Propellant Residuals	7,816.1	11,655.0	15,493.5	23,170.7	30,848.3
	Main Propellant Reserves	8,684.5	12,950.0	17,215.1	25,745.2	34,275.9
	Main Propellant Pressurant - He	14,304.8	21,330.7	28,356.0	42,406.5	56,458.0
	Stage 2 Total Inert Mass	**53,446.7**	**79,666.4**	**105,887.0**	**158,341.7**	**210,818.7**
	Fuel	133,608.1	199,230.3	264,846.9	396,079.9	527,321.5
	Oxidizer	300,618.2	448,268.1	595,905.6	891,179.8	1,186,473.4
	Stage 2 Propellant Mass	**434,226.2**	**647,498.4**	**860,752.5**	**1,287,259.7**	**1,713,794.9**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**698,834.6**	**1,042,070.3**	**1,385,277.0**	**2,071,688.8**	**2,758,145.6**
	Fuel Tank	465.4	677.1	884.4	1,290.3	1,687.9
	Oxidizer Tank	713.8	1,038.5	1,356.5	1,979.1	2,588.9
	Fore Inter-Stage Adapter	236.7	333.3	425.4	600.6	767.5
	Aft Skirt	236.7	333.3	425.4	600.6	767.5
	Inter-Tank Adapter	236.7	333.3	425.4	600.6	767.5
	Thrust Structure	8,868.7	13,589.1	18,418.5	28,311.8	38,437.2
	Oxidizer Tank Insulation	1,297.2	1,680.5	2,020.9	2,623.1	3,157.8
	Base Heat Shield	50.0	66.4	81.3	108.3	132.7
	Main Engines	39,778.4	59,332.9	78,888.0	118,004.0	157,129.0
	Propellant Feed Lines	218.5	325.8	433.1	647.8	862.5
	Gimbal	22,968.1	34,249.6	45,531.4	68,098.3	90,670.4
	Main Propellant Residuals	25,871.8	38,579.4	51,287.5	76,707.3	102,133.0
	Main Propellant Reserves	28,746.4	42,866.0	56,986.1	85,230.3	113,481.1
	Main Propellant Pressurant - He	47,350.0	70,607.3	93,865.3	140,388.2	186,921.8
	Stage 1 Total Inert Mass	**177,038.4**	**264,012.5**	**351,029.2**	**525,190.2**	**699,504.9**
	Fuel	442,252.5	659,477.3	876,709.0	1,311,236.0	1,745,863.3
	Oxidizer	995,068.0	1,483,823.9	1,972,595.3	2,950,281.0	3,928,192.4
	Stage 1 Total Propellant Mass	**1,437,320.5**	**2,143,301.2**	**2,849,304.3**	**4,261,517.0**	**5,674,055.7**
	Total Rocket Propellant Mass	**2,002,753.6**	**2,986,468.6**	**3,970,180.5**	**5,937,800.9**	**7,905,772.1**
	Total Rocket Inert Mass	**260,439.8**	**387,915.4**	**515,430.1**	**770,595.1**	**1,025,934.0**
	Total Rocket Mass	**2,313,193.4**	**3,449,384.0**	**4,585,610.6**	**6,858,396.0**	**9,131,706.1**

Table B 17: Baseline Parametric Rocket Sizing Model results for the two stage, N2O4/UDMH rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	2,500.0	5,000.0	10,000.0	20,000.0	35,000.0
Stage 2	Fuel Tank	14.9	24.9	44.0	80.8	134.1
	Oxidizer Tank	12.4	20.7	36.6	67.2	111.5
	Fore Inter-Stage Adapter	10.1	16.1	27.2	47.4	75.3
	Inter-Tank Adapter	10.1	16.1	27.2	47.4	75.3
	Thrust Structure	103.0	183.9	352.2	703.8	1,253.0
	Payload Fairing	500.0	1,000.0	2,000.0	4,000.0	7,000.0
	Base Heat Shield	2.9	4.2	6.5	10.4	15.2
	Main Engines	429.0	599.2	939.6	1,620.8	2,643.2
	Main Propellant Feed Lines	4.2	7.3	13.4	25.7	44.1
	Gimbal	354.3	609.5	1,120.1	2,141.9	3,675.6
	RCS Engines	239.1	411.3	755.8	1,445.3	2,480.2
	RCS Oxidizer Tank	0.3	0.6	1.0	1.9	3.1
	RCS Fuel Tank	0.4	0.7	1.2	2.2	3.7
	RCS Propellant Feed Lines	0.1	0.2	0.3	0.6	1.0
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	503.1	865.6	1,590.7	3,041.8	5,219.8
	Main Propellant Reserves	559.0	961.8	1,767.4	3,379.7	5,799.8
	Main Propellant Pressurant - He	856.5	1,473.6	2,707.9	5,178.1	8,885.9
	RCS Propellant	612.8	1,054.2	1,937.3	3,704.6	6,357.2
	RCS Resuduals	11.0	19.0	34.9	66.7	114.4
	RCS Reserves	12.3	21.1	38.7	74.1	127.1
	RCS Pressurant - He	18.8	32.3	59.4	113.5	194.8
	Stage 2 Total Inert Mass	**5,230.5**	**8,298.3**	**14,437.5**	**26,729.7**	**45,190.2**
	Fuel	11,180.6	19,236.0	35,348.8	67,594.5	115,995.0
	Oxidizer	16,770.8	28,854.0	53,023.3	101,391.8	173,992.5
	Stage 2 Total Propellant Mass	**27,951.4**	**48,090.0**	**88,372.1**	**168,986.3**	**289,987.6**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**35,681.9**	**61,388.3**	**112,809.6**	**215,716.0**	**370,177.8**
	Fuel Tank	94.0	156.2	276.1	507.2	842.1
	Oxidizer Tank	78.2	129.8	229.5	421.6	700.0
	Fore Inter-Stage Adapter	54.4	86.5	145.5	253.6	402.8
	Aft Skirt	54.4	86.5	145.5	253.6	402.8
	Inter-Tank Adapter	54.4	86.5	145.5	253.6	402.8
	Thrust Structure	836.2	1,489.7	2,850.2	5,694.4	10,139.3
	Base Heat Shield	11.6	17.1	26.3	41.7	61.2
	Main Engines	1,870.9	3,074.2	5,482.6	10,305.7	17,550.0
	Propellant Feed Lines	30.2	51.8	95.2	181.9	312.2
	Gimbal	2,517.0	4,322.1	7,934.7	15,169.2	26,035.8
	Main Propellant Residuals	3,574.5	6,137.9	11,268.3	21,542.3	36,974.3
	Main Propellant Reserves	3,971.7	6,819.9	12,520.3	23,935.9	41,082.5
	Main Propellant Pressurant - He	6,085.1	10,448.9	19,182.6	36,672.6	62,943.3
	Stage 1 Total Inert Mass	**19,232.7**	**32,907.1**	**60,302.5**	**115,233.3**	**197,849.0**
	Fuel	79,433.7	136,398.2	250,406.5	478,717.8	821,650.1
	Oxidizer	119,150.6	204,597.3	375,609.7	718,076.7	1,232,475.2
	Stage 1 Total Propellant Mass	**198,584.3**	**340,995.5**	**626,016.2**	**1,196,794.5**	**2,054,125.3**
	Total Rocket Propellant Mass	**226,535.8**	**389,085.5**	**714,388.3**	**1,365,780.8**	**2,344,112.9**
	Total Rocket Inert Mass	**24,463.2**	**41,205.4**	**74,740.0**	**141,963.0**	**243,039.2**
	Total Rocket Mass	**253,498.9**	**435,290.9**	**799,128.4**	**1,527,743.8**	**2,622,152.1**

Table B 18: Baseline Parametric Rocket Sizing Model results for the two stage, N2O4/UDMH rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	50,000.0	75,000.0	100,000.0	150,000.0	200,000.0
Stage 2	Fuel Tank	186.1	270.7	353.7	516.1	675.3
	Oxidizer Tank	154.7	225.0	294.0	429.0	561.3
	Fore Inter-Stage Adapter	101.5	142.9	182.4	257.6	329.2
	Inter-Tank Adapter	101.5	142.9	182.4	257.6	329.2
	Thrust Structure	1,818.7	2,786.7	3,777.4	5,807.8	7,886.5
	Payload Fairing	10,000.0	15,000.0	20,000.0	30,000.0	40,000.0
	Base Heat Shield	19.5	25.9	31.7	42.3	51.8
	Main Engines	3,666.2	5,372.1	7,078.8	10,494.1	13,911.2
	Main Propellant Feed Lines	62.5	93.2	123.9	185.3	246.8
	Gimbal	5,210.1	7,768.9	10,329.0	15,451.9	20,577.6
	RCS Engines	3,515.6	5,242.3	6,969.8	10,426.6	13,885.3
	RCS Oxidizer Tank	4.3	6.2	8.2	11.9	15.6
	RCS Fuel Tank	5.2	7.5	9.8	14.3	18.7
	RCS Propellant Feed Lines	1.4	2.0	2.7	4.1	5.4
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	7,399.0	11,032.9	14,668.5	21,943.7	29,222.9
	Main Propellant Reserves	8,221.1	12,258.7	16,298.3	24,381.9	32,469.8
	Main Propellant Pressurant - He	12,595.7	18,781.8	24,971.0	37,355.9	49,747.6
	RCS Propellant	9,011.2	13,436.9	17,864.8	26,725.3	35,590.6
	RCS Resuduals	162.2	241.9	321.6	481.1	640.6
	RCS Reserves	180.2	268.7	357.3	534.5	711.8
	RCS Pressurant - He	276.1	411.7	547.4	818.9	1,090.6
	Stage 2 Total Inert Mass	**63,668.8**	**94,495.1**	**125,348.6**	**187,115.8**	**248,944.0**
	Fuel	164,421.8	245,174.5	325,966.5	487,637.6	649,397.0
	Oxidizer	246,632.6	367,761.8	488,949.8	731,456.4	974,095.5
	Stage 2 Total Propellant Mass	**411,054.4**	**612,936.3**	**814,916.3**	**1,219,094.0**	**1,623,492.5**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**524,723.2**	**782,431.4**	**1,040,264.9**	**1,556,209.8**	**2,072,436.5**
	Fuel Tank	1,168.5	1,700.5	2,222.1	3,244.1	4,246.0
	Oxidizer Tank	971.3	1,413.5	1,847.1	2,696.6	3,529.5
	Fore Inter-Stage Adapter	543.2	765.2	976.9	1,380.0	1,764.5
	Aft Skirt	543.2	765.2	976.9	1,380.0	1,764.5
	Inter-Tank Adapter	543.2	765.2	976.9	1,380.0	1,764.5
	Thrust Structure	14,721.2	22,564.6	30,597.0	47,067.8	63,940.3
	Base Heat Shield	78.5	104.3	127.7	170.1	208.6
	Main Engines	24,802.4	36,902.3	49,014.1	73,263.9	97,540.3
	Propellant Feed Lines	442.7	660.3	878.2	1,314.4	1,751.1
	Gimbal	36,914.4	55,064.3	73,231.9	109,606.6	146,021.2
	Main Propellant Residuals	52,423.2	78,198.4	103,998.8	155,655.6	207,369.0
	Main Propellant Reserves	58,248.0	86,887.1	115,554.3	172,950.7	230,410.0
	Main Propellant Pressurant - He	89,242.9	133,121.3	177,042.8	264,980.9	353,015.4
	Stage 1 Total Inert Mass	**280,642.7**	**418,912.1**	**557,444.6**	**835,090.8**	**1,113,324.8**
	Fuel	1,164,960.9	1,737,742.1	2,311,085.2	3,459,013.8	4,608,200.3
	Oxidizer	1,747,441.4	2,606,613.2	3,466,627.8	5,188,520.7	6,912,300.4
	Stage 1 Total Propellant Mass	**2,912,402.3**	**4,344,355.3**	**5,777,713.0**	**8,647,534.5**	**11,520,500.6**
	Total Rocket Propellant Mass	**3,323,456.7**	**4,957,291.6**	**6,592,629.3**	**9,866,628.5**	**13,143,993.1**
	Total Rocket Inert Mass	**344,311.5**	**513,407.2**	**682,793.2**	**1,022,206.6**	**1,362,268.7**
	Total Rocket Mass	**3,717,768.2**	**5,545,698.8**	**7,375,422.6**	**11,038,835.1**	**14,706,261.9**

Table B 19: Light-Weight Parametric Rocket Sizing Model results for the two stage, N2O4/UDMH rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	**2,500.0**	**5,000.0**	**10,000.0**	**20,000.0**	**35,000.0**
Stage 2	Fuel Tank	14.5	24.0	42.4	77.7	128.9
	Oxidizer Tank	12.1	20.0	35.2	64.6	107.2
	Fore Inter-Stage Adapter	7.4	11.7	19.7	34.3	54.4
	Inter-Tank Adapter	7.4	11.7	19.7	34.3	54.4
	Thrust Structure	99.6	176.8	337.6	673.3	1,197.6
	Payload Fairing	375.0	750.0	1,500.0	3,000.0	5,250.0
	Base Heat Shield	2.8	4.1	6.4	10.1	14.8
	Main Engines	421.7	584.6	910.5	1,562.7	2,541.7
	Main Propellant Feed Lines	4.1	7.0	12.9	24.6	42.3
	Gimbal	343.3	587.6	1,076.4	2,054.8	3,523.3
	RCS Engines	231.7	396.5	726.4	1,386.5	2,377.5
	RCS Oxidizer Tank	0.3	0.6	1.0	1.8	3.0
	RCS Fuel Tank	0.4	0.7	1.2	2.2	3.6
	RCS Propellant Feed Lines	0.1	0.2	0.3	0.5	0.9
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	487.5	834.5	1,528.7	2,918.0	5,003.6
	Main Propellant Reserves	541.7	927.2	1,698.5	3,242.3	5,559.5
	Main Propellant Pressurant - He	830.0	1,420.6	2,602.3	4,967.5	8,517.8
	RCS Propellant	593.8	1,016.3	1,861.8	3,553.9	6,093.9
	RCS Resuduals	10.7	18.3	33.5	64.0	109.7
	RCS Reserves	11.9	20.3	37.2	71.1	121.9
	RCS Pressurant - He	18.2	31.1	57.0	108.9	186.7
	Stage 2 Total Inert Mass	**4,990.2**	**7,819.8**	**13,484.6**	**24,829.0**	**41,868.7**
	Fuel	10,834.2	18,543.8	33,970.5	64,845.1	111,190.5
	Oxidizer	16,251.3	27,815.8	50,955.7	97,267.7	166,785.8
	Stage 2 Total Propellant Mass	**27,085.5**	**46,359.6**	**84,926.2**	**162,112.8**	**277,976.3**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**34,575.7**	**59,179.4**	**108,410.8**	**206,941.8**	**354,845.0**
	Fuel Tank	91.2	150.7	265.8	487.4	808.7
	Oxidizer Tank	75.8	125.3	220.9	405.2	672.2
	Fore Inter-Stage Adapter	39.7	62.8	105.4	183.4	291.1
	Aft Skirt	39.7	62.8	105.4	183.4	291.1
	Inter-Tank Adapter	39.7	62.8	105.4	183.4	291.1
	Thrust Structure	807.7	1,431.0	2,728.9	5,442.2	9,682.7
	Base Heat Shield	11.4	16.6	25.6	40.5	59.4
	Main Engines	1,817.2	2,967.9	5,271.6	9,885.7	16,817.1
	Propellant Feed Lines	29.2	49.9	91.4	174.4	299.0
	Gimbal	2,436.6	4,162.5	7,618.2	14,539.3	24,936.4
	Main Propellant Residuals	3,460.3	5,911.3	10,818.8	20,647.7	35,412.9
	Main Propellant Reserves	3,844.8	6,568.2	12,020.9	22,941.9	39,347.6
	Main Propellant Pressurant - He	5,890.6	10,063.2	18,417.4	35,149.7	60,285.2
	Stage 1 Total Inert Mass	**18,583.9**	**31,635.1**	**57,795.7**	**110,264.2**	**189,194.4**
	Fuel	76,895.3	131,363.1	240,417.6	458,838.2	786,952.4
	Oxidizer	115,342.9	197,044.7	360,626.4	688,257.3	1,180,428.5
	Stage 1 Total Propellant Mass	**192,238.2**	**328,407.8**	**601,043.9**	**1,147,095.4**	**1,967,380.9**
	Total Rocket Propellant Mass	**219,323.7**	**374,767.4**	**685,970.1**	**1,309,208.2**	**2,245,357.2**
	Total Rocket Inert Mass	**23,574.1**	**39,454.9**	**71,280.3**	**135,093.2**	**231,063.1**
	Total Rocket Mass	**245,397.7**	**419,222.4**	**767,250.5**	**1,464,301.4**	**2,511,420.3**

Table B 20: Light-Weight Parametric Rocket Sizing Model results for the two stage, N2O4/UDMH rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	50,000.0	75,000.0	100,000.0	150,000.0	200,000.0
Stage 2	Fuel Tank	178.8	260.1	339.7	495.7	648.5
	Oxidizer Tank	148.6	216.2	282.4	412.0	539.1
	Fore Inter-Stage Adapter	73.4	103.3	131.9	186.2	238.0
	Inter-Tank Adapter	73.4	103.3	131.9	186.2	238.0
	Thrust Structure	1,737.8	2,662.0	3,608.0	5,546.8	7,531.7
	Payload Fairing	7,500.0	11,250.0	15,000.0	22,500.0	30,000.0
	Base Heat Shield	18.9	25.1	30.8	41.0	50.2
	Main Engines	3,521.3	5,154.9	6,789.3	10,060.0	13,332.6
	Main Propellant Feed Lines	59.9	89.3	118.7	177.5	236.4
	Gimbal	4,992.7	7,443.1	9,894.7	14,800.8	19,709.6
	RCS Engines	3,369.0	5,022.4	6,676.7	9,987.2	13,299.6
	RCS Oxidizer Tank	4.1	6.0	7.8	11.4	15.0
	RCS Fuel Tank	5.0	7.2	9.4	13.8	18.0
	RCS Propellant Feed Lines	1.3	2.0	2.6	3.9	5.2
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	7,090.3	10,570.2	14,051.8	21,019.0	27,990.2
	Main Propellant Reserves	7,878.1	11,744.6	15,613.1	23,354.4	31,100.2
	Main Propellant Pressurant - He	12,070.2	17,994.2	23,921.1	35,781.8	47,649.2
	RCS Propellant	8,635.3	12,873.4	17,113.7	25,599.1	34,089.3
	RCS Resuduals	155.4	231.7	308.0	460.8	613.6
	RCS Reserves	172.7	257.5	342.3	512.0	681.8
	RCS Pressurant - He	264.6	394.5	524.4	784.4	1,044.6
	Stage 2 Total Inert Mass	**58,927.1**	**87,387.0**	**115,874.4**	**172,909.9**	**230,006.6**
	Fuel	157,562.9	234,892.6	312,262.1	467,088.8	622,004.1
	Oxidizer	236,344.3	352,338.9	468,393.1	700,633.2	933,006.2
	Stage 2 Total Propellant Mass	**393,907.2**	**587,231.5**	**780,655.2**	**1,167,722.0**	**1,555,010.3**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**502,834.3**	**749,618.5**	**996,529.6**	**1,490,631.9**	**1,985,016.9**
	Fuel Tank	1,121.8	1,632.3	2,132.8	3,113.5	4,075.1
	Oxidizer Tank	932.5	1,356.8	1,772.9	2,588.1	3,387.4
	Fore Inter-Stage Adapter	392.5	552.8	705.7	996.9	1,274.6
	Aft Skirt	392.5	552.8	705.7	996.9	1,274.6
	Inter-Tank Adapter	392.5	552.8	705.7	996.9	1,274.6
	Thrust Structure	14,054.1	21,537.4	29,201.5	44,917.8	61,018.2
	Base Heat Shield	76.1	101.1	123.8	164.9	202.2
	Main Engines	23,756.6	35,335.4	46,926.1	70,134.0	93,368.5
	Propellant Feed Lines	423.9	632.2	840.7	1,258.1	1,676.1
	Gimbal	35,345.7	52,713.8	70,099.9	104,911.8	139,763.5
	Main Propellant Residuals	50,195.5	74,860.5	99,551.0	148,988.3	198,482.3
	Main Propellant Reserves	55,772.7	83,178.3	110,612.2	165,542.6	220,535.9
	Main Propellant Pressurant - He	85,450.4	127,439.0	169,471.0	253,630.8	337,887.1
	Stage 1 Total Inert Mass	**268,306.8**	**400,445.1**	**532,849.1**	**798,240.7**	**1,064,219.9**
	Fuel	1,115,454.9	1,663,565.8	2,212,244.8	3,310,851.8	4,410,717.9
	Oxidizer	1,673,182.3	2,495,348.7	3,318,367.1	4,966,277.8	6,616,076.8
	Stage 1 Total Propellant Mass	**2,788,637.1**	**4,158,914.4**	**5,530,611.9**	**8,277,129.6**	**11,026,794.7**
	Total Rocket Propellant Mass	**3,182,544.4**	**4,746,145.9**	**6,311,267.1**	**9,444,851.6**	**12,581,804.9**
	Total Rocket Inert Mass	**327,233.9**	**487,832.1**	**648,723.5**	**971,150.6**	**1,294,226.6**
	Total Rocket Mass	**3,559,778.3**	**5,308,978.0**	**7,059,990.7**	**10,566,002.2**	**14,076,031.5**

Table B 21: Baseline Parametric Rocket Sizing Model results for the three stage, N2O4/UDMH rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	2,500.0	5,000.0	10,000.0	20,000.0	35,000.0
Stage 3	Fuel Tank	5.6	9.3	16.5	30.3	50.3
	Oxidizer Tank	4.7	7.7	13.7	25.2	41.8
	Fore Inter-Stage Adapter	4.1	6.6	11.1	19.3	30.7
	Inter-Tank Adapter	4.1	6.6	11.1	19.3	30.7
	Thrust Structure	41.9	74.8	143.3	286.2	509.4
	Payload Fairing	500.0	1,000.0	2,000.0	4,000.0	7,000.0
	Base Heat Shield	1.4	2.0	3.1	4.9	7.2
	Main Engines	294.6	367.9	514.5	807.7	1,247.7
	Propellant Feed Lines	1.5	2.6	4.7	9.0	15.5
	Gimbal	152.7	262.6	482.5	922.4	1,582.3
	RCS Engines	103.0	177.2	325.6	622.4	1,067.7
	RCS Oxidizer Tank	0.2	0.3	0.5	0.8	1.4
	RCS Fuel Tank	0.2	0.3	0.6	1.0	1.7
	Propellant Feed Lines	0.0	0.1	0.1	0.2	0.4
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	176.9	304.4	559.2	1,069.0	1,833.8
	Main Propellant Reserves	196.6	338.2	621.3	1,187.7	2,037.6
	Main Propellant Pressurant - He	301.2	518.1	951.9	1,819.8	3,121.8
	RCS Propellant	264.1	454.2	834.5	1,595.3	2,736.8
	RCS Resuduals	4.8	8.2	15.0	28.7	49.3
	RCS Reserves	5.3	9.1	16.7	31.9	54.7
	RCS Pressurant - He	8.1	13.9	25.6	48.9	83.9
	Stage 3 Total Inert Mass	**3,046.9**	**4,540.1**	**7,527.5**	**13,506.2**	**22,480.7**
	Fuel	3,931.9	6,763.7	12,426.4	23,754.8	40,752.1
	Oxidizer	5,897.8	10,145.5	18,639.6	35,632.3	61,128.1
	Stage 3 Total Propellant Mass	**9,829.7**	**16,909.1**	**31,066.1**	**59,387.1**	**101,880.2**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**15,376.6**	**26,449.3**	**48,593.5**	**92,893.3**	**159,360.9**
	Fuel Tank	17.8	29.4	51.9	95.2	157.8
	Oxidizer Tank	14.8	24.4	43.1	79.1	131.2
	Fore Inter-Stage Adapter	11.9	18.8	31.6	55.0	87.3
	Inter-Tank Adapter	11.9	18.8	31.6	55.0	87.3
	Thrust Structure	155.9	276.7	528.1	1,053.2	1,873.1
	Base Heat Shield	3.3	4.8	7.4	11.7	17.2
	Main Engines	540.9	788.6	1,284.0	2,275.4	3,763.3
	Propellant Feed Lines	5.1	8.7	16.0	30.6	52.4
	Gimbal	522.1	893.6	1,636.8	3,123.8	5,355.7
	Main Propellant Residuals	605.1	1,035.7	1,896.9	3,620.4	6,207.1
	Main Propellant Reserves	672.4	1,150.8	2,107.7	4,022.6	6,896.7
	Main Propellant Pressurant - He	1,030.2	1,763.1	3,229.2	6,163.2	10,566.6
	Stage 2 Total Inert Mass	**3,591.3**	**6,013.5**	**10,864.4**	**20,585.1**	**35,195.8**
	Fuel	13,447.7	23,015.1	42,153.8	80,452.7	137,934.7
	Oxidizer	20,171.5	34,522.7	63,230.7	120,679.0	206,902.0
	Stage 2 Propellant Mass	**33,619.1**	**57,537.8**	**105,384.5**	**201,131.7**	**344,836.7**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**52,587.1**	**90,000.6**	**164,842.5**	**314,610.1**	**539,393.4**
	Fuel Tank	55.9	92.4	163.0	298.8	495.6
	Oxidizer Tank	46.5	76.8	135.5	248.4	412.0
	Fore Inter-Stage Adapter	33.8	53.6	89.9	156.4	248.2
	Aft Skirt	33.8	53.6	89.9	156.4	248.2
	Inter-Tank Adapter	33.8	53.6	89.9	156.4	248.2
	Thrust Structure	574.8	1,018.9	1,943.1	3,874.0	6,890.0
	Base Heat Shield	7.8	11.5	17.6	27.9	41.0
	Main Engines	1,374.1	2,211.8	3,888.1	7,243.5	12,281.4
	Propellant Feed Lines	17.3	29.6	54.2	103.5	177.5
	Gimbal	1,771.9	3,028.5	5,542.8	10,576.0	18,132.9
	Main Propellant Residuals	2,053.6	3,509.9	6,423.9	12,257.2	21,015.2
	Main Propellant Reserves	2,281.8	3,899.9	7,137.7	13,619.1	23,350.2
	Main Propellant Pressurant - He	3,495.9	5,975.1	10,935.8	20,866.0	35,775.3
	Stage 1 Total Inert Mass	**11,781.2**	**20,015.2**	**36,511.5**	**69,583.7**	**119,315.6**
	Fuel	45,635.1	77,997.8	142,753.7	272,381.5	467,004.2
	Oxidizer	68,452.6	116,996.8	214,130.5	408,572.2	700,506.3
	Stage 1 Total Propellant Mass	**114,087.7**	**194,994.6**	**356,884.2**	**680,953.7**	**1,167,510.5**
	Total Rocket Propellant Mass	**157,536.5**	**269,441.6**	**493,334.8**	**941,472.5**	**1,614,227.3**
	Total Rocket Inert Mass	**18,419.4**	**30,568.9**	**54,903.3**	**103,675.0**	**176,992.2**
	Total Rocket Mass	**178,456.0**	**305,010.5**	**558,238.1**	**1,065,147.5**	**1,826,219.5**

Table B 22: Baseline Parametric Rocket Sizing Model results for the three stage, N2O4/UDMH rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	50,000.0	75,000.0	100,000.0	150,000.0	200,000.0
Stage 3	Fuel Tank	69.7	101.4	132.5	193.2	252.8
	Oxidizer Tank	58.0	84.3	110.1	160.6	210.1
	Fore Inter-Stage Adapter	41.4	58.3	74.4	105.0	134.2
	Inter-Tank Adapter	41.4	58.3	74.4	105.0	134.2
	Thrust Structure	739.2	1,132.2	1,534.4	2,358.4	3,201.7
	Payload Fairing	10,000.0	15,000.0	20,000.0	30,000.0	40,000.0
	Base Heat Shield	9.3	12.3	15.1	20.1	24.6
	Main Engines	1,687.8	2,421.4	3,155.2	4,623.0	6,091.2
	Propellant Feed Lines	21.9	32.7	43.5	65.0	86.6
	Gimbal	2,242.4	3,342.9	4,443.5	6,645.3	8,847.5
	RCS Engines	1,513.1	2,255.7	2,998.4	4,484.1	5,970.1
	RCS Oxidizer Tank	1.9	2.8	3.7	5.4	7.1
	RCS Fuel Tank	2.3	3.4	4.4	6.5	8.5
	Propellant Feed Lines	0.6	0.9	1.2	1.7	2.3
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	2,598.9	3,874.2	5,149.8	7,701.6	10,253.9
	Main Propellant Reserves	2,887.7	4,304.7	5,722.0	8,557.3	11,393.2
	Main Propellant Pressurant - He	4,424.2	6,595.3	8,766.8	13,110.8	17,455.8
	RCS Propellant	3,878.5	5,781.7	7,685.4	11,493.5	15,302.5
	RCS Resuduals	69.8	104.1	138.3	206.9	275.4
	RCS Reserves	77.6	115.6	153.7	229.9	306.1
	RCS Pressurant - He	118.8	177.2	235.5	352.2	468.9
	Stage 3 Total Inert Mass	**31,460.6**	**46,435.5**	**61,418.4**	**91,401.7**	**121,402.8**
	Fuel	57,753.1	86,094.0	114,440.6	171,146.3	227,864.6
	Oxidizer	86,629.6	129,141.0	171,660.9	256,719.4	341,796.9
	Stage 3 Total Propellant Mass	**144,382.6**	**215,235.0**	**286,101.5**	**427,865.7**	**569,661.5**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**225,843.3**	**336,670.6**	**447,519.9**	**669,267.3**	**891,064.3**
	Fuel Tank	218.9	318.3	415.7	606.6	793.5
	Oxidizer Tank	181.9	264.6	345.6	504.2	659.6
	Fore Inter-Stage Adapter	117.7	165.7	211.4	298.5	381.5
	Inter-Tank Adapter	117.7	165.7	211.4	298.5	381.5
	Thrust Structure	2,717.7	4,162.5	5,641.3	8,671.7	11,773.8
	Base Heat Shield	22.1	29.3	35.9	47.8	58.5
	Main Engines	5,252.0	7,734.2	10,217.4	15,186.1	20,157.2
	Propellant Feed Lines	74.3	110.7	147.2	220.1	293.1
	Gimbal	7,588.7	11,312.0	15,036.8	22,490.0	29,946.6
	Main Propellant Residuals	8,795.0	13,110.1	17,427.0	26,064.9	34,706.7
	Main Propellant Reserves	9,772.2	14,566.8	19,363.4	28,961.0	38,563.0
	Main Propellant Pressurant - He	14,972.2	22,318.0	29,667.0	44,371.6	59,083.1
	Stage 2 Total Inert Mass	**49,830.2**	**74,257.8**	**98,720.1**	**147,720.8**	**196,798.2**
	Fuel	195,443.9	291,335.5	387,267.2	579,219.2	771,260.7
	Oxidizer	293,165.9	437,003.2	580,900.8	868,828.9	1,156,891.1
	Stage 2 Propellant Mass	**488,609.8**	**728,338.6**	**968,168.0**	**1,448,048.1**	**1,928,151.8**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**764,283.2**	**1,139,267.0**	**1,514,408.0**	**2,265,036.3**	**3,016,014.4**
	Fuel Tank	687.3	999.8	1,306.0	1,905.8	2,493.7
	Oxidizer Tank	571.3	831.1	1,085.6	1,584.2	2,072.9
	Fore Inter-Stage Adapter	334.6	471.1	601.3	849.1	1,085.3
	Aft Skirt	334.6	471.1	601.3	849.1	1,085.3
	Inter-Tank Adapter	334.6	471.1	601.3	849.1	1,085.3
	Thrust Structure	9,997.8	15,315.7	20,759.8	31,919.1	43,345.9
	Base Heat Shield	52.5	69.7	85.4	113.7	139.4
	Main Engines	17,323.1	25,731.8	34,146.0	50,986.6	67,839.6
	Propellant Feed Lines	251.5	374.9	498.4	745.7	993.1
	Gimbal	25,695.4	38,308.4	50,929.7	76,190.7	101,470.2
	Main Propellant Residuals	29,779.8	44,397.7	59,025.3	88,301.7	117,599.4
	Main Propellant Reserves	33,088.6	49,330.8	65,583.7	98,113.0	130,666.0
	Main Propellant Pressurant - He	50,695.7	75,580.6	100,481.9	150,320.6	200,195.8
	Stage 1 Total Inert Mass	**169,146.8**	**252,353.8**	**335,705.8**	**502,728.4**	**670,072.0**
	Fuel	661,772.9	986,615.9	1,311,673.1	1,962,259.1	2,613,320.7
	Oxidizer	992,659.4	1,479,923.9	1,967,509.7	2,943,388.7	3,919,981.0
	Stage 1 Total Propellant Mass	**1,654,432.3**	**2,466,539.8**	**3,279,182.8**	**4,905,647.8**	**6,533,301.7**
	Total Rocket Propellant Mass	**2,287,424.7**	**3,410,113.4**	**4,533,452.3**	**6,781,561.6**	**9,031,115.0**
	Total Rocket Inert Mass	**250,437.6**	**373,047.1**	**495,844.3**	**741,850.9**	**988,273.0**
	Total Rocket Mass	**2,587,862.3**	**3,858,160.6**	**5,129,296.5**	**7,673,412.4**	**10,219,388.1**

Table B 23: Light-Weight Parametric Rocket Sizing Model results for the three stage, N2O4/UDMH rockets capable of 2,500-35,000 kg to LEO, all values are in kg

	Payload	2,500.0	5,000.0	10,000.0	20,000.0	35,000.0
Stage 3	Fuel Tank	5.4	9.0	15.9	29.2	48.3
	Oxidizer Tank	4.5	7.5	13.2	24.2	40.2
	Fore Inter-Stage Adapter	3.0	4.8	8.1	14.0	22.2
	Inter-Tank Adapter	3.0	4.8	8.1	14.0	22.2
	Thrust Structure	40.6	72.0	137.4	274.0	487.1
	Payload Fairing	375.0	750.0	1,500.0	3,000.0	5,250.0
	Base Heat Shield	1.3	2.0	3.0	4.8	7.0
	Main Engines	291.5	361.7	502.1	783.1	1,204.6
	Propellant Feed Lines	1.4	2.5	4.5	8.7	14.9
	Gimbal	148.0	253.3	464.0	885.4	1,517.6
	RCS Engines	99.9	170.9	313.1	597.4	1,024.1
	RCS Oxidizer Tank	0.2	0.3	0.4	0.8	1.3
	RCS Fuel Tank	0.2	0.3	0.5	1.0	1.6
	Propellant Feed Lines	0.0	0.1	0.1	0.2	0.4
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	171.6	293.6	537.7	1,026.1	1,758.8
	Main Propellant Reserves	190.6	326.2	597.5	1,140.1	1,954.3
	Main Propellant Pressurant - He	292.1	499.8	915.4	1,746.8	2,994.2
	RCS Propellant	256.1	438.2	802.5	1,531.3	2,624.8
	RCS Resuduals	4.6	7.9	14.4	27.6	47.2
	RCS Reserves	5.1	8.8	16.0	30.6	52.5
	RCS Pressurant - He	7.8	13.4	24.6	46.9	80.4
	Stage 3 Total Inert Mass	**2,878.2**	**4,203.1**	**6,854.6**	**12,162.0**	**20,129.9**
	Fuel	3,812.8	6,524.7	11,949.4	22,801.9	39,085.4
	Oxidizer	5,719.2	9,787.1	17,924.1	34,202.8	58,628.1
	Stage 3 Total Propellant Mass	**9,532.0**	**16,311.8**	**29,873.5**	**57,004.7**	**97,713.4**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**14,910.2**	**25,514.9**	**46,728.2**	**89,166.7**	**152,843.3**
	Fuel Tank	17.3	28.4	50.0	91.6	151.7
	Oxidizer Tank	14.3	23.6	41.6	76.1	126.1
	Fore Inter-Stage Adapter	8.7	13.7	22.9	39.8	63.2
	Inter-Tank Adapter	8.7	13.7	22.9	39.8	63.2
	Thrust Structure	150.8	266.2	506.4	1,007.9	1,790.9
	Base Heat Shield	3.2	4.7	7.2	11.4	16.7
	Main Engines	530.4	767.5	1,241.9	2,191.4	3,616.5
	Propellant Feed Lines	5.0	8.4	15.4	29.3	50.3
	Gimbal	506.3	862.0	1,573.6	2,997.8	5,135.4
	Main Propellant Residuals	586.8	999.0	1,823.8	3,474.3	5,951.7
	Main Propellant Reserves	652.0	1,110.0	2,026.4	3,860.4	6,613.1
	Main Propellant Pressurant - He	998.9	1,700.6	3,104.7	5,914.6	10,132.0
	Stage 2 Total Inert Mass	**3,482.3**	**5,797.9**	**10,436.9**	**19,734.4**	**33,710.7**
	Fuel	13,039.7	22,199.8	40,528.2	77,207.5	132,261.0
	Oxidizer	19,559.5	33,299.7	60,792.4	115,811.3	198,391.5
	Stage 2 Propellant Mass	**32,599.2**	**55,499.6**	**101,320.6**	**193,018.8**	**330,652.6**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**50,991.7**	**86,812.4**	**158,485.7**	**301,919.9**	**517,206.6**
	Fuel Tank	54.3	89.3	157.0	287.4	476.3
	Oxidizer Tank	45.1	74.3	130.5	238.9	395.9
	Fore Inter-Stage Adapter	24.7	38.9	65.2	113.2	179.5
	Aft Skirt	24.7	38.9	65.2	113.2	179.5
	Inter-Tank Adapter	24.7	38.9	65.2	113.2	179.5
	Thrust Structure	556.0	980.0	1,862.4	3,705.8	6,585.3
	Base Heat Shield	7.7	11.2	17.2	27.1	39.8
	Main Engines	1,337.8	2,139.6	3,744.2	6,956.6	11,780.1
	Propellant Feed Lines	16.8	28.6	52.1	99.3	170.1
	Gimbal	1,717.5	2,920.1	5,327.1	10,145.7	17,380.8
	Main Propellant Residuals	1,990.5	3,384.3	6,173.8	11,758.4	20,143.6
	Main Propellant Reserves	2,211.7	3,760.3	6,859.8	13,064.9	22,381.8
	Main Propellant Pressurant - He	3,388.6	5,761.2	10,510.1	20,017.0	34,291.6
	Stage 1 Total Inert Mass	**11,400.2**	**19,265.7**	**35,029.8**	**66,640.8**	**114,183.8**
	Fuel	44,233.9	75,206.0	137,196.4	261,298.0	447,636.2
	Oxidizer	66,350.9	112,809.1	205,794.6	391,947.1	671,454.3
	Stage 1 Total Propellant Mass	**110,584.8**	**188,015.1**	**342,991.0**	**653,245.1**	**1,119,090.5**
	Total Rocket Propellant Mass	**152,716.1**	**259,826.5**	**474,185.2**	**903,268.5**	**1,547,456.5**
	Total Rocket Inert Mass	**17,760.7**	**29,266.7**	**52,321.3**	**98,537.2**	**168,024.5**
	Total Rocket Mass	**172,976.7**	**294,093.1**	**536,506.5**	**1,021,805.7**	**1,750,480.9**

Table B 24: : Light-Weight Parametric Rocket Sizing Model results for the three stage, N2O4/UDMH rockets capable of 50,000-200,000 kg to LEO, all values are in kg

	Payload	**50,000.0**	**75,000.0**	**100,000.0**	**150,000.0**	**200,000.0**
Stage 3	Fuel Tank	67.0	97.5	127.3	185.7	242.8
	Oxidizer Tank	55.7	81.0	105.8	154.3	201.9
	Fore Inter-Stage Adapter	30.0	42.2	53.8	76.0	97.1
	Inter-Tank Adapter	30.0	42.2	53.8	76.0	97.1
	Thrust Structure	706.7	1,082.2	1,466.4	2,253.5	3,059.2
	Payload Fairing	7,500.0	11,250.0	15,000.0	22,500.0	30,000.0
	Base Heat Shield	9.0	12.0	14.6	19.5	23.9
	Main Engines	1,626.2	2,329.0	3,032.0	4,438.3	5,844.9
	Propellant Feed Lines	21.0	31.4	41.7	62.3	83.0
	Gimbal	2,150.0	3,204.3	4,258.7	6,368.2	8,478.1
	RCS Engines	1,450.8	2,162.2	2,873.7	4,297.1	5,720.8
	RCS Oxidizer Tank	1.9	2.7	3.6	5.2	6.8
	RCS Fuel Tank	2.3	3.3	4.3	6.2	8.2
	Propellant Feed Lines	0.6	0.8	1.1	1.7	2.2
	Guidance Navigation	243.0	243.0	243.0	243.0	243.0
	Communication and Tracking	359.0	359.0	359.0	359.0	359.0
	Data Processing	61.0	61.0	61.0	61.0	61.0
	Thermal Control System	294.0	294.0	294.0	294.0	294.0
	Ordinance	19.0	19.0	19.0	19.0	19.0
	Main Propellant Residuals	2,491.8	3,713.6	4,935.7	7,380.4	9,825.7
	Main Propellant Reserves	2,768.6	4,126.2	5,484.1	8,200.5	10,917.5
	Main Propellant Pressurant - He	4,241.9	6,321.9	8,402.3	12,564.1	16,726.9
	RCS Propellant	3,718.6	5,542.0	7,365.8	11,014.3	14,663.5
	RCS Resuduals	66.9	99.8	132.6	198.3	263.9
	RCS Reserves	74.4	110.8	147.3	220.3	293.3
	RCS Pressurant - He	113.9	169.8	225.7	337.5	449.3
	Stage 3 Total Inert Mass	**28,103.2**	**41,400.7**	**54,706.3**	**81,335.2**	**107,982.0**
	Fuel	55,372.8	82,524.5	109,681.9	164,009.4	218,349.6
	Oxidizer	83,059.1	123,786.7	164,522.9	246,014.2	327,524.5
	Stage 3 Total Propellant Mass	**138,431.9**	**206,311.2**	**274,204.9**	**410,023.6**	**545,874.1**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**216,535.1**	**322,711.9**	**428,911.1**	**641,358.7**	**853,856.0**
	Fuel Tank	210.3	305.8	399.4	582.7	762.2
	Oxidizer Tank	174.8	254.2	332.0	484.3	633.6
	Fore Inter-Stage Adapter	85.1	119.8	152.9	215.8	275.8
	Inter-Tank Adapter	85.1	119.8	152.9	215.8	275.8
	Thrust Structure	2,597.5	3,977.4	5,389.8	8,283.9	11,246.7
	Base Heat Shield	21.4	28.4	34.8	46.3	56.8
	Main Engines	5,042.3	7,419.7	9,798.2	14,557.5	19,319.1
	Propellant Feed Lines	71.2	106.1	141.0	210.9	280.8
	Gimbal	7,274.1	10,840.3	14,408.1	21,547.0	28,689.4
	Main Propellant Residuals	8,430.4	12,563.4	16,698.3	24,972.0	33,249.7
	Main Propellant Reserves	9,367.1	13,959.4	18,553.7	27,746.7	36,944.1
	Main Propellant Pressurant - He	14,351.5	21,387.4	28,426.4	42,511.2	56,602.7
	Stage 2 Total Inert Mass	**47,711.0**	**71,081.9**	**94,487.4**	**141,374.0**	**188,336.7**
	Fuel	187,342.3	279,187.6	371,073.3	554,933.2	738,882.2
	Oxidizer	281,013.4	418,781.4	556,609.9	832,399.8	1,108,323.3
	Stage 2 Propellant Mass	**468,355.7**	**697,969.0**	**927,683.2**	**1,387,333.0**	**1,847,205.6**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**732,601.8**	**1,091,762.8**	**1,451,081.7**	**2,170,065.8**	**2,889,398.3**
	Fuel Tank	660.3	960.3	1,254.3	1,830.2	2,394.7
	Oxidizer Tank	548.9	798.3	1,042.7	1,521.4	1,990.6
	Fore Inter-Stage Adapter	242.0	340.6	434.7	613.7	784.4
	Aft Skirt	242.0	340.6	434.7	613.7	784.4
	Inter-Tank Adapter	242.0	340.6	434.7	613.7	784.4
	Thrust Structure	9,552.3	14,629.4	19,827.2	30,481.7	41,392.0
	Base Heat Shield	50.9	67.6	82.8	110.2	135.1
	Main Engines	16,607.3	24,658.7	32,715.7	48,841.9	64,980.3
	Propellant Feed Lines	241.0	359.2	477.4	714.2	951.1
	Gimbal	24,621.7	36,698.9	48,784.4	72,973.6	97,181.2
	Main Propellant Residuals	28,535.5	42,532.4	56,538.9	84,573.2	112,628.7
	Main Propellant Reserves	31,706.1	47,258.2	62,821.0	93,970.2	125,143.0
	Main Propellant Pressurant - He	48,577.5	72,405.1	96,249.2	143,973.4	191,733.9
	Stage 1 Total Inert Mass	**161,827.6**	**241,389.9**	**321,097.6**	**480,831.1**	**640,884.0**
	Fuel	634,122.6	945,163.8	1,256,420.0	1,879,403.5	2,502,860.4
	Oxidizer	951,183.9	1,417,745.7	1,884,630.0	2,819,105.3	3,754,290.6
	Stage 1 Total Propellant Mass	**1,585,306.5**	**2,362,909.5**	**3,141,050.0**	**4,698,508.8**	**6,257,150.9**
	Total Rocket Propellant Mass	**2,192,094.1**	**3,267,189.7**	**4,342,938.0**	**6,495,865.4**	**8,650,230.6**
	Total Rocket Inert Mass	**237,641.8**	**353,872.5**	**470,291.2**	**703,540.3**	**937,202.6**
	Total Rocket Mass	**2,479,735.9**	**3,696,062.1**	**4,913,229.3**	**7,349,405.7**	**9,787,433.2**

Table B 25: Baseline Parametric Rocket Sizing Model results for the four stage, solid rockets capable of 500-1,500 kg to LEO, all values are in kg

	Payload	500.0	750.0	1000.0	1,250.0	1,500.0
Stage 4	Case	22.9	33.6	45.0	57.0	69.6
	Insulation	12.0	17.0	22.3	27.7	33.3
	Nozzle	24.7	33.2	41.7	50.1	58.5
	Igniter	1.6	1.8	2.0	2.2	2.4
	Fore Inter-Stage Adapter	0.4	0.6	0.7	0.8	1.0
	Payload Fairing	100.0	150.0	200.0	250.0	300.0
	Onboard Computers	236.8	236.8	236.8	236.8	236.8
	RCS Engines	14.3	19.4	24.6	29.8	35.0
	RCS Oxidizer Tank	0.0	0.0	0.0	0.0	0.1
	RCS Fuel Tank	0.0	0.0	0.0	0.1	0.1
	RCS Propellant Feed Lines	0.0	0.0	0.0	0.0	0.0
	RCS Propellant	36.6	49.8	63.0	76.3	89.6
	RCS Resuduals	0.7	0.9	1.1	1.4	1.6
	RCS Reserves	0.7	1.0	1.3	1.5	1.8
	RCS Pressurant - He	1.1	1.5	1.9	2.3	2.7
	Stage 4 Total Inert Mass	**451.7**	**545.6**	**640.4**	**736.0**	**832.3**
	Stage 4 Total Propellant Mass	**1,176.8**	**1,602.4**	**2028.9**	**2,456.3**	**2,884.5**
Stage 3	**Stage 3 Payload (Stage 4 Total Mass)**	**2,128.5**	**2,898.0**	**3669.3**	**4,442.3**	**5,216.8**
	Case	68.0	100.0	134.4	170.7	208.8
	Insulation	32.6	46.5	61.1	76.1	91.6
	Igniter	2.4	2.9	3.4	3.9	4.4
	Nozzle	57.4	77.5	97.4	117.3	137.1
	Fore Inter-Stage Adapter	0.9	1.2	1.5	1.8	2.0
	Stage 3 Total Inert Mass	**161.4**	**228.1**	**297.7**	**369.8**	**443.9**
	Stage 3 Total Propellant Mass	**2,832.2**	**3,866.4**	**4906.4**	**5,951.5**	**7,001.2**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**5,122.1**	**6,992.6**	**8873.4**	**10,763.6**	**12,661.9**
	Case	204.0	301.4	406.3	517.8	635.0
	Insulation	89.7	128.5	169.2	211.5	255.2
	Igniter	4.3	5.5	6.8	8.0	9.2
	Nozzle	134.7	182.3	229.9	277.5	325.1
	Fore Inter-Stage Adapter	2.0	2.6	3.2	3.8	4.4
	Stage 2 Total Inert Mass	**434.8**	**620.4**	**815.5**	**1,018.7**	**1,229.0**
	Stage 2 Total Propellant Mass	**6,872.7**	**9,415.6**	**11983.1**	**14,572.2**	**17,180.2**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**12,429.5**	**17,028.6**	**21672.0**	**26,354.4**	**31,071.2**
	Case	620.7	922.0	1249.0	1,598.0	1,966.6
	Insulation	249.9	359.8	475.8	597.0	722.8
	Igniter	9.1	12.1	15.2	18.3	21.5
	Nozzle	319.4	434.2	549.4	665.2	781.4
	Fore Inter-Stage Adapter	4.3	5.7	7.0	8.4	9.6
	Aft Skirt	4.3	5.7	7.0	8.4	9.6
	Stage 1 Total Inert Mass	**1,207.8**	**1,739.6**	**2303.5**	**2,895.2**	**3,511.5**
	Stage 1 Total Propellant Mass	**16,866.6**	**23,212.4**	**29652.7**	**36,175.8**	**42,771.6**
	Total Rocket Propellant Mass	**27,748.3**	**38,096.9**	**48571.1**	**59,155.7**	**69,837.6**
	Total Rocket Inert Mass	**2,255.6**	**3,133.7**	**4057.1**	**5,019.6**	**6,016.8**
	Total Rocket Mass	**30,503.9**	**41,980.6**	**36864.9**	**65,425.4**	**77,354.3**

Table B 26: Baseline Parametric Rocket Sizing Model results for the four stage, solid rockets capable of 1,750-5,000 kg to LEO, all values are in kg

	Payload	1,750.0	2,000.0	2,250.0	2,500.0	5,000.0
Stage 4	Case	82.6	96.1	110.0	124.2	282.6
	Insulation	39.0	44.8	50.8	56.8	121.1
	Nozzle	66.8	75.1	83.4	91.7	173.4
	Igniter	2.6	2.8	3.0	3.2	5.3
	Fore Inter-Stage Adapter	1.1	1.2	1.3	1.4	2.5
	Payload Fairing	350.0	400.0	450.0	500.0	1,000.0
	Onboard Computers	236.8	236.8	236.8	236.8	236.8
	RCS Engines	40.2	45.4	50.6	55.8	108.3
	RCS Oxidizer Tank	0.1	0.1	0.1	0.1	0.2
	RCS Fuel Tank	0.1	0.1	0.1	0.1	0.2
	RCS Propellant Feed Lines	0.0	0.0	0.0	0.0	0.0
	RCS Propellant	102.9	116.3	129.6	143.0	277.6
	RCS Resuduals	1.9	2.1	2.3	2.6	5.0
	RCS Reserves	2.1	2.3	2.6	2.9	5.6
	RCS Pressurant - He	3.2	3.6	4.0	4.4	8.5
	Stage 4 Total Inert Mass	**929.2**	**1,026.6**	**1,124.5**	**1,222.9**	**2,227.0**
	Stage 4 Total Propellant Mass	**3,313.6**	**3,743.2**	**4,173.6**	**4,604.4**	**8,938.4**
Stage 3	**Stage 3 Payload (Stage 4 Total Mass)**	**5,992.7**	**6,769.8**	**7,548.1**	**8,327.3**	**16,165.4**
	Case	248.4	289.4	331.7	375.2	863.3
	Insulation	107.5	123.8	140.4	157.2	338.6
	Igniter	4.9	5.4	5.9	6.4	11.5
	Nozzle	156.9	176.7	196.4	216.1	412.5
	Fore Inter-Stage Adapter	2.3	2.6	2.8	3.1	5.5
	Stage 3 Total Inert Mass	**520.0**	**597.8**	**677.2**	**758.0**	**1,631.5**
	Stage 3 Total Propellant Mass	**8,054.9**	**9,112.2**	**10,172.9**	**11,236.7**	**22,011.1**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**14,567.6**	**16,479.8**	**18,398.1**	**20,322.0**	**39,808.0**
	Case	757.4	884.5	1,015.9	1,151.3	2,687.5
	Insulation	300.2	346.3	393.4	441.5	963.6
	Igniter	10.5	11.8	13.0	14.3	27.4
	Nozzle	372.7	420.4	468.1	515.8	995.7
	Fore Inter-Stage Adapter	5.0	5.6	6.1	6.7	12.0
	Stage 2 Total Inert Mass	**1,445.8**	**1,668.4**	**1,896.5**	**2,129.6**	**4,686.0**
	Stage 2 Total Propellant Mass	**19,805.2**	**22,445.6**	**25,100.2**	**27,768.0**	**55,029.9**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**35,818.6**	**40,593.9**	**45,394.8**	**50,219.6**	**99,523.9**
	Case	2,353.0	2,755.7	3,173.6	3,605.7	8,575.1
	Insulation	852.6	986.1	1,123.0	1,263.1	2,804.8
	Igniter	24.7	27.9	31.2	34.4	68.2
	Nozzle	898.1	1,015.2	1,132.7	1,250.7	2,449.4
	Fore Inter-Stage Adapter	10.9	12.2	13.4	14.7	26.7
	Aft Skirt	10.9	12.2	13.4	14.7	26.7
	Stage 1 Total Inert Mass	**4,150.2**	**4,809.2**	**5,487.3**	**6,183.2**	**13,950.9**
	Stage 1 Total Propellant Mass	**49,433.0**	**56,154.3**	**62,930.7**	**69,758.7**	**140,344.8**
	Total Rocket Propellant Mass	**80,606.7**	**91,455.3**	**102,377.4**	**113,367.8**	**226,324.1**
	Total Rocket Inert Mass	**7,045.1**	**8,102.0**	**9,185.5**	**10,293.7**	**22,495.4**
	Total Rocket Mass	**89,401.8**	**101,557.4**	**113,812.9**	**126,161.5**	**253,819.5**

Table B 27: Light-Weight Parametric Rocket Sizing Model results for the four stage, solid rockets capable of 500-1,500 kg to LEO, all values are in kg

	Payload	**500.0**	**750.0**	**1,000.0**	**1,250.0**	**1,500.0**
Stage 4	Case	16.4	23.9	32.0	40.4	49.3
	Insulation	11.5	16.2	21.2	26.3	31.6
	Nozzle	23.8	31.9	40.0	48.0	55.9
	Igniter	1.6	1.8	2.0	2.1	2.3
	Fore Inter-Stage Adapter	0.3	0.4	0.5	0.6	0.7
	Payload Fairing	75.0	112.5	150.0	187.5	225.0
	Onboard Computers	236.8	236.8	236.8	236.8	236.8
	RCS Engines	13.7	18.6	23.5	28.4	33.4
	RCS Oxidizer Tank	0.0	0.0	0.0	0.0	0.1
	RCS Fuel Tank	0.0	0.0	0.0	0.1	0.1
	RCS Propellant Feed Lines	0.0	0.0	0.0	0.0	0.0
	RCS Propellant	35.2	47.8	60.3	72.9	85.5
	RCS Resuduals	0.6	0.9	1.1	1.3	1.5
	RCS Reserves	0.7	1.0	1.2	1.5	1.7
	RCS Pressurant - He	1.1	1.5	1.8	2.2	2.6
	Stage 4 Total Inert Mass	**416.8**	**493.3**	**570.5**	**648.2**	**726.4**
	Stage 4 Total Propellant Mass	**1,133.8**	**1,537.7**	**1,942.3**	**2,347.7**	**2,753.6**
Stage 3	**Stage 3 Payload (Stage 4 Total Mass)**	**2,050.6**	**2,780.9**	**3,512.8**	**4,245.9**	**4,980.1**
	Case	48.2	70.5	94.3	119.5	145.9
	Insulation	31.0	43.9	57.5	71.5	85.9
	Igniter	2.3	2.8	3.2	3.7	4.2
	Nozzle	55.0	73.8	92.6	111.2	129.8
	Fore Inter-Stage Adapter	0.7	0.9	1.1	1.3	1.5
	Stage 3 Total Inert Mass	**137.1**	**191.9**	**248.7**	**307.2**	**367.2**
	Stage 3 Total Propellant Mass	**2,705.7**	**3,676.8**	**4,652.2**	**5,631.2**	**6,613.5**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**4,893.3**	**6,649.6**	**8,413.6**	**10,184.3**	**11,960.8**
	Case	142.7	209.4	281.1	357.0	436.6
	Insulation	84.1	119.8	157.0	195.7	235.6
	Igniter	4.1	5.3	6.4	7.5	8.7
	Nozzle	127.6	171.8	215.9	259.9	303.9
	Fore Inter-Stage Adapter	1.4	1.9	2.3	2.7	3.1
	Stage 2 Total Inert Mass	**360.1**	**508.2**	**662.7**	**822.8**	**987.8**
	Stage 2 Total Propellant Mass	**6,497.4**	**8,852.7**	**11,225.6**	**13,613.5**	**16,014.7**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**11,750.8**	**16,010.5**	**20,301.9**	**24,620.7**	**28,963.2**
	Case	427.1	629.3	847.5	1,079.6	1,323.7
	Insulation	230.9	329.9	433.9	542.2	654.3
	Igniter	8.6	11.3	14.1	16.9	19.8
	Nozzle	298.8	403.5	508.4	613.4	718.5
	Fore Inter-Stage Adapter	3.1	4.0	4.9	5.8	6.7
	Aft Skirt	3.1	4.0	4.9	5.8	6.7
	Stage 1 Total Inert Mass	**971.4**	**1,382.0**	**1,813.8**	**2,263.8**	**2,729.8**
	Stage 1 Total Propellant Mass	**15,734.8**	**21,510.9**	**27,352.7**	**33,250.5**	**39,197.6**
	Total Rocket Propellant Mass	**26,071.7**	**35,578.1**	**45,172.7**	**54,843.0**	**64,579.4**
	Total Rocket Inert Mass	**1,885.4**	**2,575.4**	**3,295.7**	**4,042.0**	**4,811.2**
	Total Rocket Mass	**28,457.1**	**38,903.5**	**49,468.4**	**60,135.0**	**70,890.6**

Table B 28: Light-Weight Parametric Rocket Sizing Model results for the four stage, solid rockets capable of 1,750-5,000 kg to LEO, all values are in kg

	Payload	1,750.0	2,000.0	2250.0	2,500.0	5,000.0
Stage 4	Case	58.4	67.9	77.6	87.6	198.5
	Insulation	37.0	42.4	48.0	53.7	114.0
	Nozzle	63.8	71.7	79.6	87.4	164.9
	Igniter	2.5	2.7	2.9	3.1	5.1
	Fore Inter-Stage Adapter	0.8	0.9	0.9	1.0	1.8
	Payload Fairing	262.5	300.0	337.5	375.0	750.0
	Onboard Computers	236.8	236.8	48.2	236.8	236.8
	RCS Engines	38.3	43.2	0.1	53.1	102.7
	RCS Oxidizer Tank	0.1	0.1	0.1	0.1	0.2
	RCS Fuel Tank	0.1	0.1	0.0	0.1	0.2
	RCS Propellant Feed Lines	0.0	0.0	236.8	0.0	0.0
	RCS Propellant	98.1	110.8	123.4	136.1	263.3
	RCS Resuduals	1.8	2.0	2.2	2.5	4.7
	RCS Reserves	2.0	2.2	2.5	2.7	5.3
	RCS Pressurant - He	3.0	3.4	3.8	4.2	8.1
	Stage 4 Total Inert Mass	**805.1**	**884.2**	**963.6**	**1,043.4**	**1,855.6**
	Stage 4 Total Propellant Mass	**3,160.1**	**3,567.1**	**3974.6**	**4,382.4**	**8,478.9**
Stage 3	**Stage 3 Payload (Stage 4 Total Mass)**	**5,715.2**	**6,451.3**	**7188.1**	**7,925.8**	**15,334.5**
	Case	173.3	201.6	230.8	260.8	596.0
	Insulation	100.6	115.7	131.0	146.6	313.8
	Igniter	4.6	5.1	5.6	6.1	10.9
	Nozzle	148.4	166.9	185.3	203.8	386.9
	Fore Inter-Stage Adapter	1.6	1.8	2.0	2.2	3.9
	Stage 3 Total Inert Mass	**428.6**	**491.1**	**554.7**	**619.4**	**1,311.3**
	Stage 3 Total Propellant Mass	**7,598.6**	**8,586.3**	**9576.4**	**10,568.6**	**20,587.4**
Stage 2	**Stage 2 Payload (Stage 3 Total Mass)**	**13,742.4**	**15,528.7**	**17319.3**	**19,113.8**	**37,233.2**
	Case	519.5	605.4	694.2	785.5	1,814.3
	Insulation	276.5	318.4	361.1	404.6	874.6
	Igniter	9.8	11.0	12.2	13.3	25.2
	Nozzle	347.8	391.6	435.5	479.3	917.6
	Fore Inter-Stage Adapter	3.5	3.9	4.3	4.7	8.3
	Stage 2 Total Inert Mass	**1,157.1**	**1,330.3**	**1507.2**	**1,687.5**	**3,640.2**
	Stage 2 Total Propellant Mass	**18,427.6**	**20,851.1**	**23284.5**	**25,726.9**	**50,552.0**
Stage 1	**Stage 1 Payload (Stage 2 Total Mass)**	**33,327.0**	**37,710.1**	**42111.0**	**46,528.3**	**91,425.4**
	Case	1,578.9	1,844.1	2118.6	2,401.8	5,623.9
	Insulation	769.6	887.8	1008.9	1,132.4	2,478.9
	Igniter	22.7	25.5	28.5	31.4	61.3
	Nozzle	823.8	929.3	1034.9	1,140.7	2,207.3
	Fore Inter-Stage Adapter	7.6	8.4	9.3	10.1	18.2
	Aft Skirt	7.6	8.4	9.3	10.1	18.2
	Stage 1 Total Inert Mass	**3,210.1**	**3,703.7**	**4209.4**	**4,726.6**	**10,407.9**
	Stage 1 Total Propellant Mass	**45,188.9**	**51,220.3**	**57288.8**	**63,391.6**	**125,946.7**
	Total Rocket Propellant Mass	**74,375.2**	**84,224.9**	**94,124.2**	**104,069.6**	**205,565.0**
	Total Rocket Inert Mass	**5,600.9**	**6,409.3**	**7,235.0**	**8,076.9**	**17,215.0**
	Total Rocket Mass	**81,726.1**	**92,634.2**	**103,609.2**	**114,646.4**	**227,779.9**

APPENDIX C: LIFE CYCLE INVENTORY

Table C 1: Life cycle inventory entries into SimaPro for Structural Materials

Material	Life Cycle Inventory Entry	EcoInvent Identifier Number	Manufacturing Entry	EcoInvent Identifier Number
Aluminum (Wrought)	Aluminium, production mix, wrought alloy, at plant/RER S	EIN_SYSX06573800992	Aluminium product manufacturing, average metal working/RER S	EIN_SYSX08490409108
Low Alloy Steel	Steel, low-alloyed, at plant/RER S	EIN_SYSX06573801085	Steel product manufacturing, average metal working/RER S	EIN_SYSX08490409136
Stainless Steel	Steel, electric, chromium steel 18/8, at plant/RER S	EIN_SYSX06573801083	Chromium steel product manufacturing, average metal working/RER S	EIN_SYSX08490409107
Iron-Nickle-Chromium Steel	Iron-nickel-chromium alloy, at plant/RER S	EIN_SYSX08490407491	Steel product manufacturing, average metal working/RER S	EIN_SYSX08490409136
Titanium	**Table C 6**		Metal product manufacturing, average metal working/RER S	EIN_SYSX08490409389
Cobalt	Cobalt, at plant/GLO S	EIN_SYSX06573802391	Metal product manufacturing, average metal working/RER S	EIN_SYSX08490409389
Molybdenum	Molybdenum, at regional storage/RER S	EIN_SYSX06573801050	Metal product manufacturing, average metal working/RER S	EIN_SYSX08490409389
Carbon Fiber Reinforced Polymer	**Table C 3**		**Table C 5**	
Polyurethane Foam	Polyurethane, rigid foam, at plant/RER S	EIN_SYSX06573801677	*neglected*	
Synthetic Rubber	Synthetic rubber, at plant/RER S	EIN_SYSX06573801685	*neglected*	
Glass Foam	Foam glass, at plant/RER S	EIN_SYSX08490407636	*neglected*	
Graphite	Graphite, at plant/RER S	EIN_SYSX06573800281	*neglected*	
Explosive	Explosives, tovex, at plant/CH S	EIN_SYSX06573800275	*neglected*	

Table C 2: Life cycle inventory entries into SimaPro for Propellants

Propellant	Life Cycle Inventory Entry	EcoInvent Identifier Number
Liquid Oxygen	Oxygen, liquid, at plant/RER S	EIN_SYSX06573800301
Nitrogen Tetroxide	**Table C 7**	
Liquid Hygrogen	Hydrogen, liquid, at plant/RER S	EIN_SYSX06573800286
Rocket Propellant 1	Kerosene, at refinery/RER S	EIN_SYSX06573801395
Unsymmetrical Dimethylhyrazine	**Table C 8**	
Solid	**Table C 9**	

Table C 3: The production of 1 kg of carbon fiber reinforced polymer, as input into SimaPro

Known Inputs from Technosphere (materials/fuels)		
Name	*Amount*	*Unit*
Carbon Fiber (**Table C 4)**	0.65	kg
Epoxy Resin, liquid, at plant/RER S	0.35	kg

Table C 4: SimaPro inputs for the production of 1 kg of carbon fibers

Known Inputs from Nature (resources)			
Name	*Sub-compartment*	*Amount*	*Unit*
Air	in air	240	kg
Known Inputs from Technosphere (materials/fuels)			
Name	*Amount*	*Unit*	
Polyacrylonitrile fibres (PAN) from acrylonitrile and methacrylate, prod. Mix, PAN w/o additives EU-27 S	1.718	kg	
Nitrogen, liquid, at plant/RER S	20.75	kg	
Known Inputs from Technosphere (electricity/heat)			
Name	*Amount*	*Unit*	
Electricity, production mix RER/RER S	116248.6	kJ	
Emission to Air			
Name	*Sub-compartment*	*Amount*	*Unit*
Carbon dioxide	low. pop.	0.305	kg
Carbon monoxide	low. pop.	0.054	kg
Water	low. pop.	0.409	kg
Ammonia	low. pop.	0.076	kg
Hydrogen cyanide	low. pop.	0.283	kg
Hydrogen	low. pop.	0.021	kg
Nitrogen	low. pop.	208.104	kg
Oxygen	low. pop.	50.245	kg
Argon	low. pop.	2.4	kg
Methane	low. pop.	0.027	kg

Table C 5: Manufacturing a 1 kg CFRP component using a filament winding technique, as input into SimaPro

Known Inputs from Technosphere (electricity/heat)		
Name	*Amount*	*Unit*
Electricity, production mix RER/RER S	42.7	MJ

Table C 6: The production of 1 ton of titanium using the Kroll Process, as input into SimaPro

Known Inputs from Technosphere (materials/fuels)			
Name	*Amount*	*Unit*	
Magnesium, at plant/RER S	0.016	ton	
Argon, liquid, at plant/RER S	0.178	ton	
Chlorine, liquid, production mix, at plant/RER S	0.32	ton	
Petroleum coke, at refinery/RER S	0.44	ton	
Known Inputs from Technosphere (electricity/heat)			
Name	*Amount*	*Unit*	
Electricity, production mix RER/RER S	28390	kWh	
Natural gas, high pressure, at consumer/RER S	17.5	GJ	
Emission to Air			
Name	*Sub-compartment*	*Amount*	*Unit*
Carbon dioxide	low. pop.	34.6	ton
Carbon monoxide	low. pop.	8.5	kg
Nitrogen dioxide	low. pop.	0.27	kg
Methane	low. pop.	44.8	kg
Nitrogen oxides	low. pop.	166	kg
VOC, volatile organic compounds	low. pop.	1.7	kg
Sulfur dioxide	low. pop.	0.114	ton

Table C 7: The production of 1 kg of nitrogen tetroxide, as input into SimaPro

Known Inputs from Technosphere (materials/fuels)			
Name	*Amount*	*Unit*	
Ammonia, liquid, at regional storehouse/RER S	0.531548	kg	
Oxygen, liquid, at plant/RER S	4.69393	kg	
Emissions to Air			
Name	*Sub-compartment*	*Amount*	*Unit*
Oxygen	low. pop.	3.2636	kg
Nitrogen	low. pop.	0.124296	kg
Water	low. pop.	0.826601	kg

Table C 8: The production of 1 kg of unsymmetrical dimethylhydrazine, as input into SimaPro

Known Outputs to Technosphere. Avoided Products		
Name	*Amount*	*Unit*
Dimethylamine, at plant/RER S	6.75	kg
Sodium chloride, powder, at plant/RER S	0.97293	kg
Known Inputs from Technosphere (materials/fuels)		
Name	*Amount*	*Unit*
Dimethylamine, at plant/RER S	7.5	kg
Chloramine **(Table C 10)**	0.857	kg
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	0.6659	kg

Table C 9: The production of 1 kg of solid propellant, as input into SimaPro

Known Inputs from Technosphere (materials/fuel)		
Name	*Amount*	*Unit*
Ammonium Perchlorate **(Table C 11)**	0.7	kg
Aluminum, primary, at plant/RER S	0.16	kg
Polybutadiene, at plant/RER S	0.14	kg

Table C 10: The production of 1 kg of chloramine, as input into SimaPro

Known Outputs to Technosphere. Avoided Products		
Name	*Amount*	*Unit*
Ammonia, liquid, at regional storehouse/RER S	2.43	kg
Nitrogen, liquid, at plant/RER S	0.18	kg
Known Inputs from Technosphere (materials/fuels)		
Name	*Amount*	*Unit*
Ammonia, liquid, at regional storehouse/RER S	2.65	kg
Chlorine, liquid, producton mix, at plant/RER S	0.69	kg
Nitrogen, liquid, at plant/RER S	0.27	kg
Known Inputs from Technosphere (electricity/heat)		
Name	*Amount*	*Unit*
Electricity, production mix RER/RER S	5.904	MJ

Table C 11: The production of 1 kg of ammonium perchlorate, as input into SimaPro

Known Inputs from Technosphere (materials/fuels)		
Name	*Amount*	*Unit*
Ammonia, liquid, at regional storehouse/RER S	0.14495	kg
Perchloric Acid **(Table C 12)**	0.85505	kg

Table C 12: The production of 1 kg of perchloric acid, as input into SimaPro

Known Outputs to Technosphere. Avoided Products		
Name	*Amount*	*Unit*
Sodium chloride, powder, at plant/RER S	0.581724	kg
Known Inputs from Technosphere (materials/fuels)		
Name	*Amount*	*Unit*
Sodium perchlorate, at plant/GLO S	1.2187935	kg
Hydrochloric acid, from the reaction of hydrogen with chlorine, at plant/RER S	0.3629305	kg

Table C 13: Database entries used from EcoInvent for the manually entered life cycle inventories

Entry Name	EcoInvent Identifier Number
Aluminum, primary, at plant/RER S	EIN_SYSX06573800988
Ammonia, liquid, at regional storehouse/RER S	EIN_SYSX06573800246
Argon, liquid, at plant/RER S	EIN_SYSX06573800252
Chlorine, liquid, production mix, at plant/RER S	EIN_SYSX06573800269
Dimethylamine, at plant/RER S	EIN_SYSX08490407421
Electricity, production mix RER/RER S	EIN_SYSX08490407769
Epoxy Resin, liquid, at plant/RER S	EIN_SYSX06573801640
Hydrochloric acid, from the reaction of hydrogen with chlorine, at plant/RER S	EIN_SYSX06573802443
Magnesium, at plant/RER S	EIN_SYSX06573801040
Natural gas, high pressure, at consumer/RER S	EIN_SYSX06573801231
Nitrogen, liquid, at plant/RER S	EIN_SYSX06573800300
Petroleum coke, at refinery/RER S	EIN_SYSX06573801415
Polybutadiene, at plant/RER S	EIN_SYSX06573801663
Sodium chloride, powder, at plant/RER S	EIN_SYSX06573800329
Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	EIN_SYSX06573800336

APPENDIX D: LIFE CYCLE IMPACT ASSESSMENT RESULTS

Table D 1: Life cycle environmental impacts of the baseline two stage, LOX/LH2 rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	**5,000**	**10,000**	**20,000**	**35,000**	**50,000**	**75,000**	**100,000**	**150,000**	**200,000**
Climate change	kg CO2 eq	58.030	46.044	39.861	36.618	35.134	34.506	33.979	33.712	33.387	33.264
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	4,742.031	3,322.277	2,607.163	2,246.328	2,090.160	2,027.538	1,978.278	1,954.557	1,928.848	1,919.330
Photochemical oxidant formation	kg NMVOC	0.243	0.192	0.166	0.153	0.147	0.144	0.142	0.141	0.140	0.140
Particulate matter formation	kg PM10 eq	0.238	0.194	0.172	0.161	0.156	0.154	0.152	0.151	0.151	0.150
Ionising radiation	kg U235 eq	21.660	17.029	14.660	13.434	12.883	12.653	12.464	12.370	12.257	12.217
Terrestrial acidification	kg SO2 eq	0.808	0.662	0.588	0.551	0.534	0.528	0.523	0.521	0.519	0.519
Freshwater eutrophication	kg P eq	0.078	0.056	0.045	0.040	0.037	0.036	0.035	0.035	0.035	0.034
Marine eutrophication	kg N eq	0.081	0.065	0.056	0.052	0.050	0.049	0.048	0.048	0.047	0.047
Terrestrial ecotoxicity	kg 1,4-DB eq	0.139	0.106	0.089	0.080	0.076	0.075	0.074	0.073	0.073	0.072
Freshwater ecotoxicity	kg 1,4-DB eq	1.990	1.482	1.225	1.094	1.037	1.014	0.996	0.987	0.977	0.974
Marine ecotoxicity	kg 1,4-DB eq	3,174.993	2,337.459	1,914.385	1,700.131	1,607.043	1,569.665	1,540.154	1,526.109	1,510.519	1,505.350
Agricultural land occupation	m2a	1.173	0.811	0.629	0.536	0.496	0.479	0.466	0.460	0.453	0.450
Urban land occupation	m2a	0.652	0.462	0.366	0.318	0.297	0.288	0.281	0.278	0.275	0.273
Natural land transformation	m2	0.011	0.009	0.008	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Water depletion	m3	0.547	0.411	0.341	0.304	0.288	0.281	0.275	0.272	0.269	0.268
Metal depletion	kg Fe eq	44.911	34.163	28.729	25.976	24.782	24.304	23.927	23.751	23.552	23.494
Fossil depletion	kg oil eq	28.773	23.445	20.678	19.213	18.534	18.244	17.997	17.871	17.713	17.655

Table D 2: Life cycle environmental impacts of the light-weighted two stage, LOX/LH2 rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	5,000	10,000	20,000	35,000	50,000	75,000	100,000	150,000	200,000
Climate change	kg CO2 eq	58.597	46.516	40.288	37.016	35.515	34.877	34.339	34.066	33.730	33.597
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	4,696.905	3,275.851	2,560.555	2,199.577	2,043.270	1,980.537	1,931.143	1,907.293	1,881.447	1,871.663
Photochemical oxidant formation	kg NMVOC	0.244	0.193	0.167	0.153	0.147	0.145	0.143	0.142	0.141	0.140
Particulate matter formation	kg PM10 eq	0.235	0.192	0.170	0.158	0.153	0.151	0.150	0.149	0.148	0.148
Ionising radiation	kg U235 eq	23.725	18.938	16.477	15.188	14.599	14.349	14.137	14.030	13.896	13.843
Terrestrial acidification	kg SO2 eq	0.827	0.678	0.603	0.565	0.548	0.541	0.536	0.533	0.531	0.530
Freshwater eutrophication	kg P eq	0.079	0.057	0.046	0.040	0.038	0.037	0.036	0.035	0.035	0.035
Marine eutrophication	kg N eq	0.084	0.067	0.058	0.054	0.051	0.051	0.050	0.049	0.049	0.049
Terrestrial ecotoxicity	kg 1,4-DB eq	0.131	0.098	0.082	0.073	0.070	0.068	0.067	0.067	0.066	0.066
Freshwater ecotoxicity	kg 1,4-DB eq	1.961	1.453	1.196	1.065	1.008	0.985	0.967	0.958	0.949	0.945
Marine ecotoxicity	kg 1,4-DB eq	3,129.967	2,292.116	1,869.338	1,655.271	1,562.258	1,524.890	1,495.376	1,481.292	1,465.685	1,460.349
Agricultural land occupation	m2a	1.182	0.819	0.636	0.542	0.502	0.485	0.472	0.465	0.458	0.455
Urban land occupation	m2a	0.630	0.441	0.346	0.298	0.277	0.269	0.262	0.259	0.256	0.254
Natural land transformation	m2	0.011	0.009	0.007	0.007	0.006	0.006	0.006	0.006	0.006	0.006
Water depletion	m3	-2.707	-2.634	-2.576	-2.524	-2.486	-2.464	-2.438	-2.422	-2.397	-2.384
Metal depletion	kg Fe eq	43.710	32.985	27.574	24.836	23.650	23.176	22.803	22.629	22.434	22.376
Fossil depletion	kg oil eq	29.157	23.771	20.976	19.493	18.803	18.506	18.253	18.123	17.959	17.894

Table D 3: Life cycle environmental impacts of the baseline three stage, LOX/LH2 rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	5,000	10,000	20,000	35,000	50,000	75,000	100,000	150,000	200,000
Climate change	kg CO2 eq	50.662	39.635	33.992	31.063	29.742	29.190	28.732	28.503	28.227	28.125
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	4,196.270	2,848.545	2,172.582	1,833.600	1,688.173	1,630.360	1,585.366	1,563.851	1,541.071	1,532.562
Photochemical oxidant formation	kg NMVOC	0.218	0.170	0.146	0.134	0.128	0.126	0.124	0.123	0.122	0.122
Particulate matter formation	kg PM10 eq	0.222	0.180	0.158	0.148	0.143	0.141	0.140	0.139	0.139	0.139
Ionising radiation	kg U235 eq	18.524	14.317	12.182	11.089	10.605	10.407	10.245	10.166	10.072	10.039
Terrestrial acidification	kg SO2 eq	0.762	0.619	0.548	0.512	0.497	0.491	0.486	0.485	0.483	0.483
Freshwater eutrophication	kg P eq	0.069	0.048	0.038	0.032	0.030	0.029	0.029	0.028	0.028	0.028
Marine eutrophication	kg N eq	0.066	0.052	0.044	0.040	0.039	0.038	0.037	0.037	0.037	0.037
Terrestrial ecotoxicity	kg 1,4-DB eq	0.132	0.100	0.083	0.075	0.071	0.070	0.069	0.068	0.067	0.067
Freshwater ecotoxicity	kg 1,4-DB eq	1.809	1.321	1.075	0.952	0.898	0.877	0.860	0.853	0.844	0.841
Marine ecotoxicity	kg 1,4-DB eq	2,868.395	2,066.982	1,664.275	1,461.862	1,374.844	1,340.267	1,313.297	1,300.594	1,286.793	1,282.269
Agricultural land occupation	m2a	1.100	0.747	0.569	0.479	0.440	0.425	0.412	0.406	0.400	0.397
Urban land occupation	m2a	0.606	0.421	0.328	0.282	0.262	0.253	0.247	0.244	0.241	0.240
Natural land transformation	m2	0.010	0.008	0.007	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Water depletion	m3	0.497	0.367	0.301	0.266	0.251	0.245	0.239	0.237	0.234	0.233
Metal depletion	kg Fe eq	39.613	29.470	24.374	21.816	20.721	20.288	19.952	19.797	19.626	19.578
Fossil depletion	kg oil eq	23.599	19.002	16.634	15.394	14.828	14.588	14.387	14.285	14.159	14.113

Table D 4: Life cycle environmental impacts of the light-weighted three stage, LOX/LH2 rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	5,000	10,000	20,000	35,000	50,000	75,000	100,000	150,000	200,000
Climate change	kg CO2 eq	51.216	39.664	34.487	31.547	30.219	29.662	29.200	28.695	28.686	28.582
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	4,165.503	2,812.784	2,141.142	1,802.011	1,656.443	1,598.522	1,553.400	1,529.160	1,508.848	1,500.194
Photochemical oxidant formation	kg NMVOC	0.219	0.169	0.147	0.134	0.129	0.127	0.125	0.123	0.123	0.123
Particulate matter formation	kg PM10 eq	0.220	0.177	0.156	0.146	0.141	0.139	0.138	0.137	0.136	0.136
Ionising radiation	kg U235 eq	20.372	15.967	13.889	12.761	12.255	12.045	11.870	11.721	11.677	11.639
Terrestrial acidification	kg SO2 eq	0.777	0.631	0.561	0.525	0.509	0.503	0.499	0.495	0.494	0.494
Freshwater eutrophication	kg P eq	0.070	0.049	0.038	0.033	0.031	0.030	0.029	0.029	0.029	0.028
Marine eutrophication	kg N eq	0.069	0.053	0.046	0.042	0.041	0.040	0.039	0.039	0.039	0.039
Terrestrial ecotoxicity	kg 1,4-DB eq	0.126	0.093	0.077	0.068	0.065	0.063	0.062	0.062	0.061	0.061
Freshwater ecotoxicity	kg 1,4-DB eq	1.785	1.294	1.052	0.928	0.875	0.854	0.837	0.827	0.820	0.818
Marine ecotoxicity	kg 1,4-DB eq	2,832.273	2,027.026	1,628.430	1,426.118	1,339.123	1,304.533	1,277.537	1,262.443	1,250.944	1,246.334
Agricultural land occupation	m2a	1.108	0.751	0.576	0.486	0.447	0.431	0.419	0.411	0.406	0.403
Urban land occupation	m2a	0.587	0.402	0.311	0.264	0.244	0.236	0.230	0.226	0.224	0.223
Natural land transformation	m2	0.009	0.007	0.006	0.006	0.005	0.005	0.005	0.005	0.005	0.005
Water depletion	m3	-2.353	-2.312	-2.351	-2.334	-2.317	-2.306	-2.293	-2.261	-2.270	-2.264
Metal depletion	kg Fe eq	38.639	28.496	23.427	20.876	19.784	19.353	19.019	18.855	18.695	18.647
Fossil depletion	kg oil eq	24.016	18.925	17.006	15.757	15.185	14.942	14.737	14.330	14.503	14.455

Table D 5: Life cycle environmental impacts of the baseline two stage, LOX/RP1 rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	**5,000**	**10,000**	**20,000**	**35,000**	**50,000**	**75,000**	**100,000**	**150,000**	**200,000**
Climate change	kg CO2 eq	109.418	93.166	84.565	80.169	78.233	77.451	76.815	76.526	76.147	76.079
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	6,423.685	4,889.970	4,116.979	3,733.079	3,571.576	3,509.323	3,462.278	3,441.811	3,419.740	3,415.929
Photochemical oxidant formation	kg NMVOC	0.387	0.327	0.296	0.281	0.274	0.272	0.270	0.269	0.268	0.268
Particulate matter formation	kg PM10 eq	0.385	0.332	0.305	0.292	0.287	0.285	0.284	0.284	0.284	0.284
Ionising radiation	kg U235 eq	33.597	28.296	25.434	23.981	23.348	23.095	22.892	22.800	22.683	22.662
Terrestrial acidification	kg SO2 eq	1.362	1.178	1.086	1.041	1.024	1.018	1.015	1.014	1.014	1.016
Freshwater eutrophication	kg P eq	0.108	0.084	0.072	0.066	0.063	0.062	0.061	0.061	0.061	0.061
Marine eutrophication	kg N eq	0.123	0.122	0.111	0.105	0.103	0.102	0.101	0.101	0.100	0.100
Terrestrial ecotoxicity	kg 1,4-DB eq	0.206	0.169	0.150	0.141	0.137	0.135	0.134	0.134	0.133	0.134
Freshwater ecotoxicity	kg 1,4-DB eq	2.794	2.242	1.963	1.824	1.767	1.745	1.728	1.722	1.714	1.714
Marine ecotoxicity	kg 1,4-DB eq	4,412.915	3,505.399	3,046.623	2,819.372	2,724.459	2,688.394	2,661.509	2,650.494	2,638.357	2,637.948
Agricultural land occupation	m2a	1.529	1.153	0.960	0.864	0.822	0.806	0.794	0.788	0.782	0.780
Urban land occupation	m2a	0.955	0.743	0.636	0.582	0.560	0.551	0.544	0.541	0.538	0.537
Natural land transformation	m2	0.060	0.052	0.048	0.046	0.045	0.045	0.044	0.044	0.044	0.044
Water depletion	m3	0.838	0.684	0.605	0.564	0.547	0.540	0.535	0.533	0.530	0.530
Metal depletion	kg Fe eq	61.962	50.348	44.553	41.700	40.524	40.086	39.768	39.647	39.514	39.535
Fossil depletion	kg oil eq	55.355	47.694	43.658	41.591	40.678	40.309	40.007	39.871	39.687	39.658

Table D 6: Life cycle environmental impacts of the light-weighted two stage, LOX/RP1 rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	**5,000**	**10,000**	**20,000**	**35,000**	**50,000**	**75,000**	**100,000**	**150,000**	**200,000**
Climate change	kg CO2 eq	108.049	91.156	82.576	78.185	76.248	75.462	74.822	74.528	74.144	74.069
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	6,315.230	4,769.200	3,996.821	3,612.992	3,451.299	3,388.829	3,341.511	3,320.763	3,298.416	3,294.174
Photochemical oxidant formation	kg NMVOC	0.383	0.321	0.290	0.275	0.268	0.265	0.264	0.263	0.262	0.262
Particulate matter formation	kg PM10 eq	0.377	0.323	0.296	0.283	0.278	0.277	0.275	0.275	0.275	0.275
Ionising radiation	kg U235 eq	35.070	29.345	26.439	24.951	24.293	24.025	23.806	23.704	23.571	23.541
Terrestrial acidification	kg SO2 eq	1.358	1.170	1.076	1.031	1.013	1.007	1.004	1.003	1.002	1.004
Freshwater eutrophication	kg P eq	0.107	0.083	0.071	0.065	0.062	0.061	0.060	0.060	0.060	0.060
Marine eutrophication	kg N eq	0.124	0.104	0.094	0.089	0.086	0.085	0.085	0.084	0.084	0.084
Terrestrial ecotoxicity	kg 1,4-DB eq	0.196	0.159	0.140	0.131	0.127	0.126	0.125	0.124	0.124	0.124
Freshwater ecotoxicity	kg 1,4-DB eq	2.735	2.176	1.898	1.759	1.702	1.680	1.663	1.656	1.649	1.649
Marine ecotoxicity	kg 1,4-DB eq	4,320.802	3,403.631	2,945.662	2,718.685	2,623.754	2,587.589	2,560.560	2,549.367	2,537.074	2,536.357
Agricultural land occupation	m2a	1.523	1.138	0.945	0.849	0.807	0.791	0.778	0.772	0.766	0.764
Urban land occupation	m2a	0.923	0.710	0.603	0.550	0.528	0.519	0.512	0.510	0.506	0.506
Natural land transformation	m2	0.058	0.050	0.046	0.044	0.043	0.043	0.042	0.042	0.042	0.042
Water depletion	m3	-2.219	-2.226	-2.211	-2.184	-2.159	-2.142	-2.123	-2.110	-2.089	-2.078
Metal depletion	kg Fe eq	60.125	48.517	42.737	39.892	38.718	38.281	37.962	37.840	37.707	37.724
Fossil depletion	kg oil eq	54.735	46.805	42.771	40.701	39.785	39.412	39.107	38.967	38.780	38.747

Table D 7: Life cycle environmental impacts of the baseline three stage, LOX/RP1 rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	5,000	10,000	20,000	35,000	50,000	75,000	100,000	150,000	200,000
Climate change	kg CO2 eq	82.046	68.811	62.657	58.719	57.232	56.634	56.150	55.929	55.641	55.585
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	5,090.004	3,716.085	3,037.871	2,692.096	2,549.789	2,494.928	2,453.568	2,435.253	2,416.054	2,411.722
Photochemical oxidant formation	kg NMVOC	0.303	0.252	0.229	0.215	0.209	0.208	0.206	0.205	0.205	0.205
Particulate matter formation	kg PM10 eq	0.310	0.266	0.245	0.234	0.230	0.229	0.228	0.228	0.227	0.228
Ionising radiation	kg U235 eq	25.403	20.862	18.703	17.424	16.926	16.728	16.569	16.497	16.407	16.389
Terrestrial acidification	kg SO2 eq	1.102	0.950	0.878	0.840	0.826	0.822	0.819	0.819	0.818	0.820
Freshwater eutrophication	kg P eq	0.085	0.063	0.053	0.048	0.045	0.045	0.044	0.044	0.043	0.043
Marine eutrophication	kg N eq	0.088	0.073	0.065	0.061	0.059	0.059	0.058	0.058	0.058	0.058
Terrestrial ecotoxicity	kg 1,4-DB eq	0.171	0.138	0.122	0.114	0.111	0.109	0.108	0.108	0.108	0.108
Freshwater ecotoxicity	kg 1,4-DB eq	2.241	1.755	1.518	1.394	1.345	1.326	1.312	1.306	1.300	1.299
Marine ecotoxicity	kg 1,4-DB eq	3,532.583	2,730.727	2,337.482	2,134.321	2,052.280	2,021.121	1,997.940	1,988.269	1,977.862	1,976.962
Agricultural land occupation	m2a	1.296	0.944	0.771	0.679	0.642	0.627	0.616	0.610	0.605	0.603
Urban land occupation	m2a	0.781	0.590	0.498	0.448	0.428	0.420	0.414	0.412	0.409	0.408
Natural land transformation	m2	0.042	0.037	0.034	0.032	0.032	0.031	0.031	0.031	0.031	0.031
Water depletion	m3	0.666	0.531	0.466	0.429	0.415	0.409	0.404	0.402	0.400	0.400
Metal depletion	kg Fe eq	47.792	38.013	33.191	30.777	29.801	29.439	29.177	29.076	28.968	28.980
Fossil depletion	kg oil eq	39.847	33.968	31.599	29.473	28.807	28.539	28.319	28.220	28.086	28.063

Table D 8: Life cycle environmental impacts of the light-weighted three stage, LOX/RP1 rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	**5,000**	**10,000**	**20,000**	**35,000**	**50,000**	**75,000**	**100,000**	**150,000**	**200,000**
Climate change	kg CO2 eq	81.378	68.125	61.424	58.017	56.525	55.924	55.436	55.212	54.921	54.861
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	5,022.854	3,648.598	2,963.445	2,623.886	2,481.220	2,426.103	2,384.452	2,365.889	2,346.418	2,341.760
Photochemical oxidant formation	kg NMVOC	0.300	0.250	0.224	0.212	0.207	0.205	0.203	0.203	0.202	0.202
Particulate matter formation	kg PM10 eq	0.304	0.260	0.239	0.228	0.224	0.223	0.222	0.222	0.221	0.222
Ionising radiation	kg U235 eq	26.867	22.269	19.949	18.772	18.258	18.050	17.882	17.804	17.705	17.682
Terrestrial acidification	kg SO2 eq	1.103	0.950	0.874	0.838	0.824	0.819	0.816	0.816	0.815	0.817
Freshwater eutrophication	kg P eq	0.085	0.063	0.053	0.048	0.045	0.045	0.044	0.044	0.043	0.043
Marine eutrophication	kg N eq	0.089	0.074	0.066	0.062	0.061	0.060	0.059	0.059	0.059	0.059
Terrestrial ecotoxicity	kg 1,4-DB eq	0.163	0.130	0.114	0.106	0.103	0.102	0.101	0.100	0.100	0.100
Freshwater ecotoxicity	kg 1,4-DB eq	2.198	1.713	1.472	1.352	1.302	1.283	1.269	1.263	1.257	1.256
Marine ecotoxicity	kg 1,4-DB eq	3,468.446	2,666.631	2,267.260	2,069.982	1,987.740	1,956.422	1,933.058	1,923.216	1,912.639	1,911.494
Agricultural land occupation	m2a	1.295	0.942	0.765	0.677	0.639	0.624	0.613	0.608	0.602	0.600
Urban land occupation	m2a	0.756	0.566	0.471	0.424	0.404	0.396	0.390	0.388	0.385	0.384
Natural land transformation	m2	0.041	0.035	0.032	0.031	0.030	0.030	0.030	0.030	0.029	0.029
Water depletion	m3	-2.027	-2.082	-2.099	-2.098	-2.089	-2.083	-2.073	-2.067	-2.056	-2.051
Metal depletion	kg Fe eq	46.464	36.693	31.842	29.463	28.485	28.122	27.858	27.755	27.646	27.655
Fossil depletion	kg oil eq	39.633	33.738	30.751	29.228	28.558	28.287	28.065	27.963	27.827	27.801

Table D 9: Life cycle environmental impacts of the baseline two stage, N2O4/UDMH rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	5,000	10,000	20,000	35,000	50,000	75,000	100,000	150,000	200,000
Climate change	kg CO2 eq	363.186	308.337	280.987	267.463	261.795	259.627	257.952	257.273	256.364	256.364
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	11,122.693	8,810.329	7,661.336	7,096.669	6,862.790	6,774.389	6,708.490	6,681.396	6,650.821	6,649.162
Photochemical oxidant formation	kg NMVOC	2.072	1.764	1.611	1.536	1.505	1.493	1.484	1.481	1.476	1.477
Particulate matter formation	kg PM10 eq	0.914	0.776	0.708	0.675	0.662	0.657	0.654	0.653	0.651	0.652
Ionising radiation	kg U235 eq	161.752	137.381	125.231	119.226	116.711	115.750	115.007	114.707	114.304	114.305
Terrestrial acidification	kg SO2 eq	3.097	2.631	2.402	2.292	2.248	2.233	2.222	2.219	2.216	2.219
Freshwater eutrophication	kg P eq	0.270	0.221	0.197	0.185	0.180	0.178	0.177	0.176	0.175	0.175
Marine eutrophication	kg N eq	9.495	8.149	7.478	7.147	7.009	6.956	6.915	6.899	6.877	6.877
Terrestrial ecotoxicity	kg 1,4-DB eq	0.469	0.390	0.350	0.331	0.323	0.320	0.318	0.317	0.316	0.316
Freshwater ecotoxicity	kg 1,4-DB eq	5.095	4.151	3.683	3.454	3.360	3.325	3.299	3.289	3.278	3.279
Marine ecotoxicity	kg 1,4-DB eq	8,198.450	6,655.322	5,889.551	5,514.576	5,360.424	5,302.906	5,260.520	5,243.997	5,224.849	5,226.064
Agricultural land occupation	m2a	4.794	3.922	3.488	3.273	3.184	3.149	3.123	3.112	3.099	3.098
Urban land occupation	m2a	1.646	1.317	1.152	1.072	1.038	1.025	1.016	1.012	1.007	1.007
Natural land transformation	m2	0.076	0.064	0.059	0.056	0.055	0.054	0.054	0.054	0.053	0.053
Water depletion	m3	2.312	1.932	1.742	1.649	1.611	1.596	1.585	1.581	1.575	1.576
Metal depletion	kg Fe eq	64.308	50.839	44.190	40.970	39.678	39.212	38.888	38.774	38.661	38.699
Fossil depletion	kg oil eq	127.969	108.818	99.272	94.555	92.580	91.826	91.244	91.009	90.694	90.697

Table D 10: Life cycle environmental impacts of the light-weighted two stage, N2O4/UDMH rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	5,000	10,000	20,000	35,000	50,000	75,000	100,000	150,000	200,000
Climate change	kg CO2 eq	353.974	299.103	271.773	258.257	252.588	250.418	248.741	248.056	247.149	247.134
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	10,875.180	8,562.229	7,413.520	6,848.677	6,614.452	6,525.734	6,459.491	6,432.012	6,401.185	6,398.890
Photochemical oxidant formation	kg NMVOC	2.014	1.707	1.554	1.479	1.448	1.436	1.427	1.424	1.419	1.419
Particulate matter formation	kg PM10 eq	0.890	0.752	0.684	0.651	0.638	0.633	0.630	0.629	0.627	0.628
Ionising radiation	kg U235 eq	159.237	134.768	122.573	116.535	113.997	113.022	112.265	111.954	111.539	111.528
Terrestrial acidification	kg SO2 eq	3.041	2.574	2.343	2.232	2.188	2.172	2.162	2.158	2.154	2.157
Freshwater eutrophication	kg P eq	0.265	0.216	0.191	0.179	0.174	0.173	0.171	0.170	0.170	0.170
Marine eutrophication	kg N eq	9.198	7.854	7.185	6.855	6.717	6.665	6.624	6.608	6.586	6.587
Terrestrial ecotoxicity	kg 1,4-DB eq	0.452	0.372	0.333	0.314	0.306	0.303	0.301	0.300	0.299	0.299
Freshwater ecotoxicity	kg 1,4-DB eq	4.968	4.024	3.556	3.327	3.233	3.198	3.172	3.162	3.151	3.151
Marine ecotoxicity	kg 1,4-DB eq	7,994.877	6,451.840	5,686.623	5,311.725	5,157.431	5,099.731	5,057.145	5,040.360	5,021.076	5,021.818
Agricultural land occupation	m2a	4.687	3.815	3.380	3.166	3.076	3.041	3.015	3.004	2.990	2.989
Urban land occupation	m2a	1.594	1.265	1.102	1.021	0.988	0.975	0.965	0.962	0.957	0.957
Natural land transformation	m2	0.073	0.062	0.056	0.053	0.052	0.052	0.051	0.051	0.051	0.051
Water depletion	m3	-0.826	-1.038	-1.124	-1.147	-1.142	-1.133	-1.119	-1.108	-1.090	-1.078
Metal depletion	kg Fe eq	62.540	49.081	42.440	39.223	37.929	37.462	37.135	37.018	36.903	36.936
Fossil depletion	kg oil eq	125.150	105.967	96.412	91.687	89.706	88.947	88.361	88.122	87.803	87.800

Table D 11: Life cycle environmental impacts of the baseline three stage, N2O4/UDMH rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	5,000	10,000	20,000	35,000	50,000	75,000	100,000	150,000	200,000
Climate change	kg CO2 eq	259.625	218.284	197.646	187.399	183.065	181.383	180.063	179.500	178.756	178.685
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	8,384.153	6,422.416	5,446.705	4,965.565	4,764.824	4,687.975	4,630.034	4,604.996	4,577.388	4,572.826
Photochemical oxidant formation	kg NMVOC	1.478	1.248	1.133	1.077	1.053	1.044	1.037	1.034	1.031	1.031
Particulate matter formation	kg PM10 eq	0.683	0.574	0.519	0.493	0.482	0.479	0.476	0.475	0.474	0.474
Ionising radiation	kg U235 eq	114.883	96.671	87.581	83.069	81.162	80.421	79.841	79.593	79.265	79.234
Terrestrial acidification	kg SO2 eq	2.331	1.959	1.776	1.687	1.652	1.639	1.631	1.628	1.624	1.626
Freshwater eutrophication	kg P eq	0.198	0.159	0.139	0.129	0.125	0.124	0.122	0.122	0.121	0.121
Marine eutrophication	kg N eq	6.606	5.644	5.164	4.926	4.825	4.786	4.756	4.743	4.725	4.724
Terrestrial ecotoxicity	kg 1,4-DB eq	0.357	0.291	0.258	0.242	0.236	0.233	0.231	0.231	0.230	0.230
Freshwater ecotoxicity	kg 1,4-DB eq	3.861	3.069	2.676	2.482	2.402	2.372	2.350	2.340	2.330	2.329
Marine ecotoxicity	kg 1,4-DB eq	6,195.738	4,901.615	4,258.723	3,942.717	3,811.721	3,762.119	3,725.040	3,709.684	3,692.282	3,691.054
Agricultural land occupation	m2a	3.578	2.863	2.506	2.329	2.254	2.225	2.203	2.193	2.181	2.179
Urban land occupation	m2a	1.269	0.986	0.845	0.775	0.746	0.735	0.726	0.723	0.718	0.718
Natural land transformation	m2	0.054	0.045	0.041	0.039	0.038	0.038	0.037	0.037	0.037	0.037
Water depletion	m3	1.697	1.395	1.245	1.171	1.140	1.128	1.119	1.115	1.111	1.110
Metal depletion	kg Fe eq	49.666	37.839	31.991	29.146	27.991	27.567	27.265	27.149	27.035	27.045
Fossil depletion	kg oil eq	90.970	76.668	69.530	65.988	64.492	63.911	63.456	63.263	63.006	62.984

Table D 12: Life cycle environmental impacts of the light-weighted three stage, N2O4/UDMH rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		2,500	5,000	10,000	20,000	35,000	50,000	75,000	100,000	150,000	200,000
Climate change	kg CO2 eq	253.755	212.387	191.752	181.504	177.167	175.482	174.160	173.593	172.850	172.769
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	8,226.518	6,263.943	5,288.015	4,806.482	4,605.345	4,528.197	4,469.940	4,444.591	4,416.742	4,411.719
Photochemical oxidant formation	kg NMVOC	1.441	1.210	1.096	1.039	1.016	1.007	1.000	0.997	0.993	0.993
Particulate matter formation	kg PM10 eq	0.667	0.558	0.503	0.477	0.466	0.462	0.460	0.459	0.457	0.458
Ionising radiation	kg U235 eq	113.693	95.418	86.298	81.765	79.843	79.095	78.505	78.251	77.916	77.878
Terrestrial acidification	kg SO2 eq	2.297	1.925	1.741	1.652	1.616	1.603	1.594	1.591	1.587	1.589
Freshwater eutrophication	kg P eq	0.195	0.155	0.136	0.126	0.122	0.120	0.119	0.118	0.118	0.118
Marine eutrophication	kg N eq	6.408	5.446	4.967	4.730	4.629	4.590	4.560	4.547	4.529	4.528
Terrestrial ecotoxicity	kg 1,4-DB eq	0.344	0.278	0.245	0.229	0.223	0.220	0.218	0.218	0.217	0.217
Freshwater ecotoxicity	kg 1,4-DB eq	3.776	2.984	2.590	2.397	2.317	2.286	2.264	2.254	2.244	2.243
Marine ecotoxicity	kg 1,4-DB eq	6,059.829	4,765.374	4,122.514	3,806.330	3,675.099	3,625.301	3,588.015	3,572.437	3,554.886	3,553.304
Agricultural land occupation	m2a	3.510	2.794	2.437	2.260	2.185	2.156	2.134	2.124	2.112	2.110
Urban land occupation	m2a	1.231	0.948	0.808	0.738	0.709	0.698	0.689	0.686	0.681	0.681
Natural land transformation	m2	0.052	0.044	0.039	0.037	0.036	0.036	0.036	0.036	0.036	0.035
Water depletion	m3	-1.052	-1.260	-1.354	-1.390	-1.397	-1.396	-1.391	-1.387	-1.378	-1.373
Metal depletion	kg Fe eq	48.438	36.613	30.766	27.919	26.762	26.335	26.031	25.912	25.795	25.801
Fossil depletion	kg oil eq	89.295	74.968	67.822	64.274	62.772	62.189	61.731	61.534	61.276	61.249

Table D 13: Life cycle environmental impacts of the baseline four stage, solid rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		500	750	1,000	1,250	1,500	1,750	2,000	2,250	2,500	5,000
Climate change	kg CO2 eq	371.034	337.327	321.528	312.648	306.899	303.688	301.341	299.728	298.693	298.421
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	11,546.622	9,947.104	9,173.080	8,722.621	8,425.228	8,236.010	8,094.701	7,989.736	7,911.990	7,665.754
Photochemical oxidant formation	kg NMVOC	1.089	0.987	0.939	0.912	0.894	0.884	0.877	0.872	0.868	0.866
Particulate matter formation	kg PM10 eq	0.721	0.655	0.624	0.607	0.595	0.589	0.585	0.581	0.579	0.579
Ionising radiation	kg U235 eq	184.822	168.055	160.174	155.728	152.838	151.210	150.013	149.182	148.639	148.267
Terrestrial acidification	kg SO2 eq	2.234	2.026	1.928	1.873	1.837	1.816	1.801	1.791	1.784	1.778
Freshwater eutrophication	kg P eq	0.298	0.264	0.247	0.238	0.232	0.228	0.225	0.223	0.222	0.219
Marine eutrophication	kg N eq	0.365	0.331	0.315	0.306	0.300	0.296	0.294	0.292	0.291	0.290
Terrestrial ecotoxicity	kg 1,4-DB eq	0.521	0.467	0.442	0.427	0.418	0.412	0.408	0.405	0.404	0.401
Freshwater ecotoxicity	kg 1,4-DB eq	5.474	4.838	4.535	4.361	4.248	4.180	4.129	4.093	4.068	4.015
Marine ecotoxicity	kg 1,4-DB eq	8,604.263	7,571.293	7,077.087	6,793.054	6,607.096	6,493.327	6,409.164	6,348.138	6,304.695	6,201.202
Agricultural land occupation	m2a	5.840	5.197	4.893	4.720	4.608	4.542	4.494	4.460	4.436	4.404
Urban land occupation	m2a	1.901	1.666	1.555	1.491	1.450	1.425	1.407	1.394	1.385	1.369
Natural land transformation	m2	0.051	0.047	0.044	0.043	0.042	0.042	0.042	0.041	0.041	0.041
Water depletion	m3	7.900	7.191	6.859	6.671	6.549	6.481	6.431	6.396	6.374	6.362
Metal depletion	kg Fe eq	70.581	61.625	57.414	55.047	53.540	52.652	52.022	51.591	51.308	51.209
Fossil depletion	kg oil eq	114.681	104.314	99.468	96.753	95.001	94.031	93.326	92.846	92.543	92.587

Table D 14: Life cycle environmental impacts of the light-weighted four stage, solid rockets, normalized for 1 kg to LEO, using the ReCiPe 2008 Egalitarian midpoint indicators

Impact category	Unit	Payload to LEO (kg)									
		500	**750**	**1,000**	**1,250**	**1,500**	**1,750**	**2,000**	**2,250**	**2,500**	**5,000**
Climate change	kg CO2 eq	382.838	348.411	332.580	323.888	318.689	315.514	313.493	312.206	311.497	314.059
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	11,601.776	9,989.271	9,212.840	8,763.347	8,475.886	8,282.082	8,144.075	8,042.507	7,968.200	7,752.492
Photochemical oxidant formation	kg NMVOC	1.118	1.013	0.965	0.938	0.922	0.912	0.905	0.901	0.899	0.903
Particulate matter formation	kg PM10 eq	0.741	0.674	0.643	0.625	0.615	0.609	0.605	0.602	0.601	0.606
Ionising radiation	kg U235 eq	196.438	179.214	171.355	167.083	164.562	163.055	162.123	161.555	161.275	163.173
Terrestrial acidification	kg SO2 eq	2.464	2.249	2.152	2.100	2.070	2.053	2.043	2.037	2.035	2.071
Freshwater eutrophication	kg P eq	0.305	0.270	0.254	0.245	0.239	0.235	0.233	0.231	0.230	0.228
Marine eutrophication	kg N eq	0.387	0.352	0.335	0.326	0.321	0.318	0.316	0.315	0.314	0.317
Terrestrial ecotoxicity	kg 1,4-DB eq	0.490	0.436	0.410	0.395	0.386	0.379	0.375	0.371	0.369	0.363
Freshwater ecotoxicity	kg 1,4-DB eq	5.425	4.784	4.478	4.304	4.194	4.121	4.071	4.034	4.009	3.957
Marine ecotoxicity	kg 1,4-DB eq	8,564.511	7,522.077	7,024.858	6,739.910	6,559.889	6,440.610	6,357.142	6,296.935	6,254.369	6,159.347
Agricultural land occupation	m2a	5.848	5.198	4.891	4.718	4.610	4.540	4.493	4.460	4.437	4.413
Urban land occupation	m2a	1.808	1.572	1.459	1.394	1.352	1.324	1.304	1.290	1.279	1.250
Natural land transformation	m2	0.050	0.046	0.043	0.042	0.041	0.041	0.040	0.040	0.040	0.040
Water depletion	m3	-14.183	-14.482	-14.970	-15.489	-16.001	-16.498	-16.974	-17.426	-17.863	-21.415
Metal depletion	kg Fe eq	60.842	51.964	47.623	45.065	43.395	42.240	41.394	40.752	40.262	38.403
Fossil depletion	kg oil eq	120.227	109.598	104.749	102.113	100.558	99.628	99.053	98.702	98.530	99.697

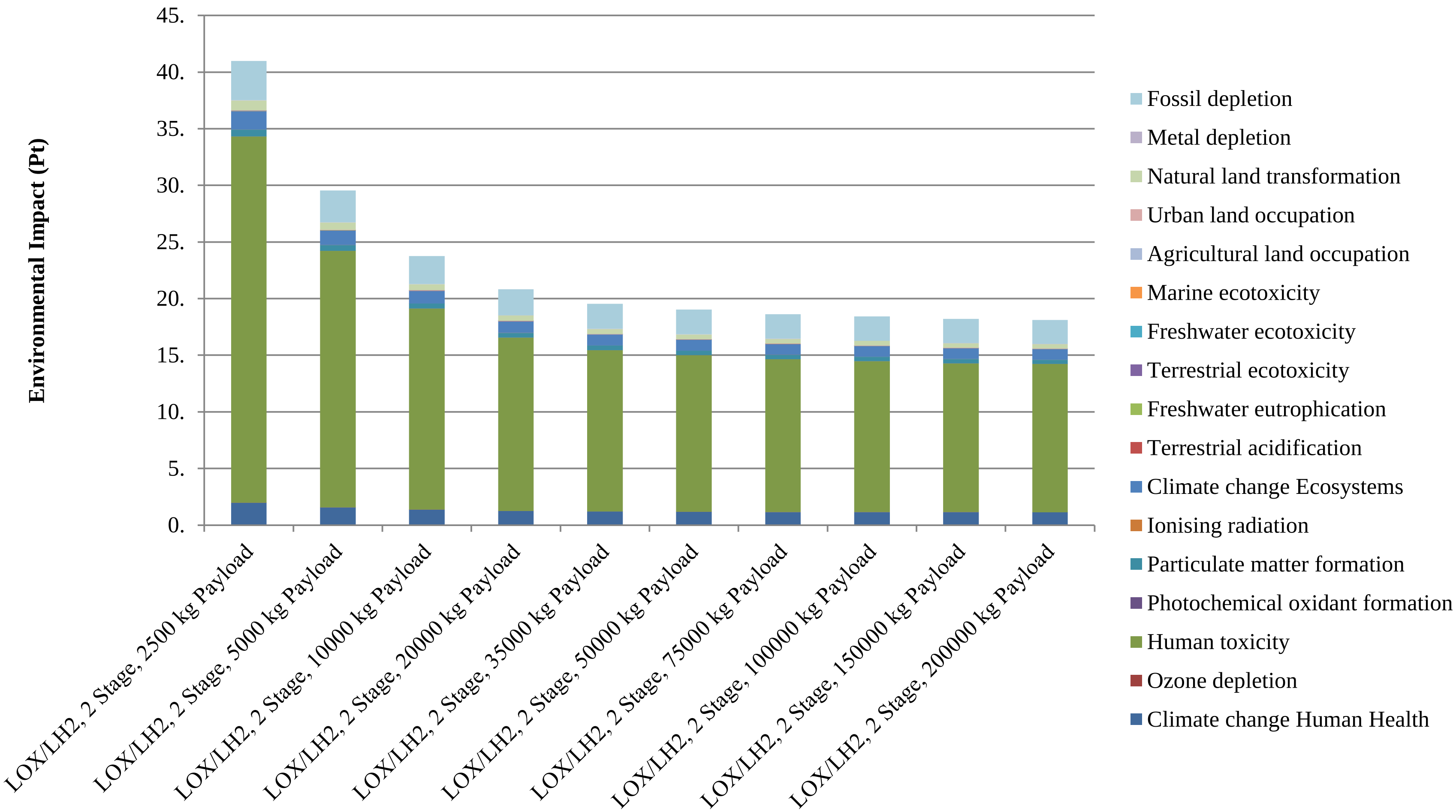


Figure D 1: Comparison of environmental impacts across lift capacities for the baseline two stage, LOX/LH2 rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

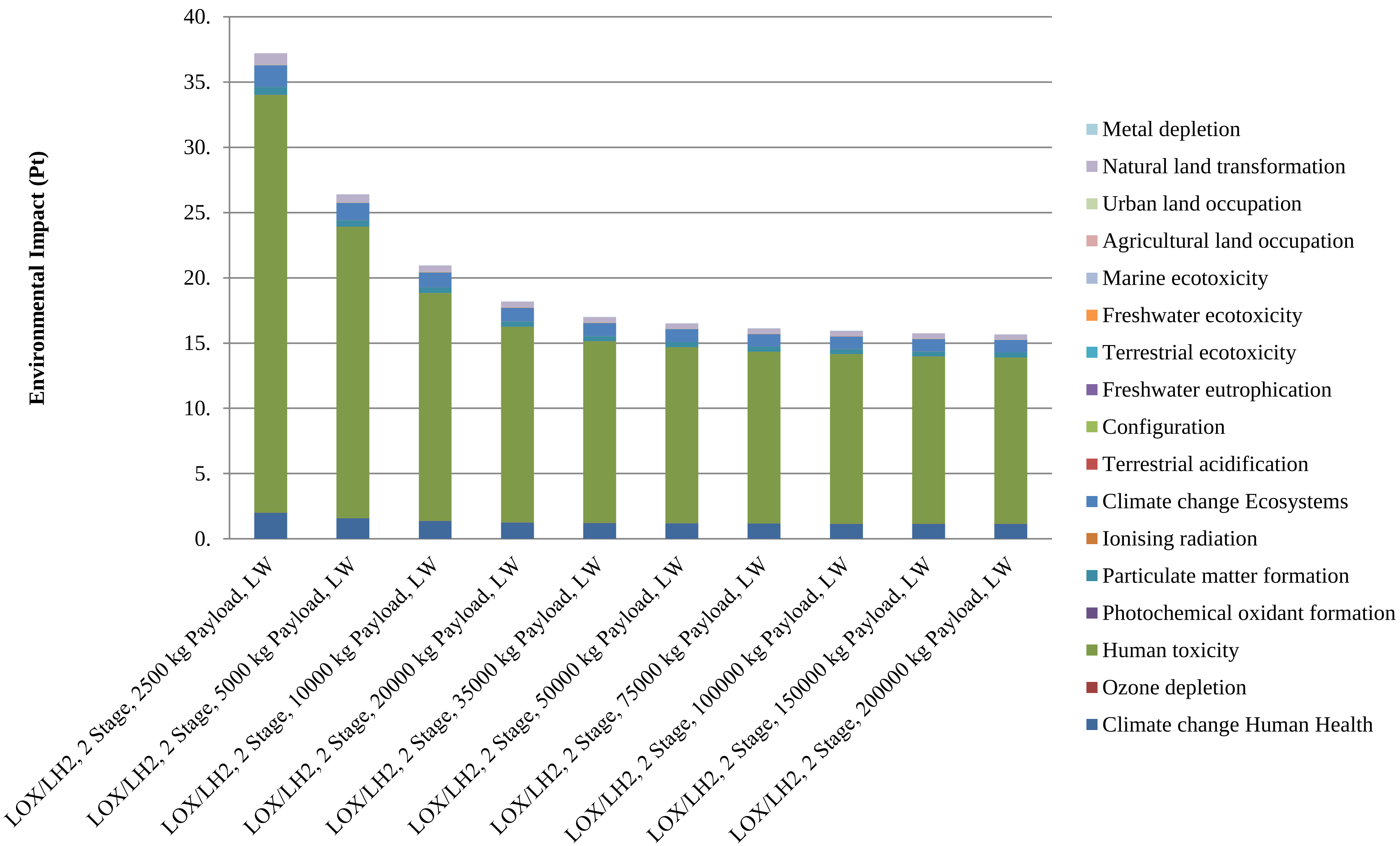


Figure D 2: Comparison of environmental impacts across lift capacities for the light-weighted two stage, LOX/LH2 rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

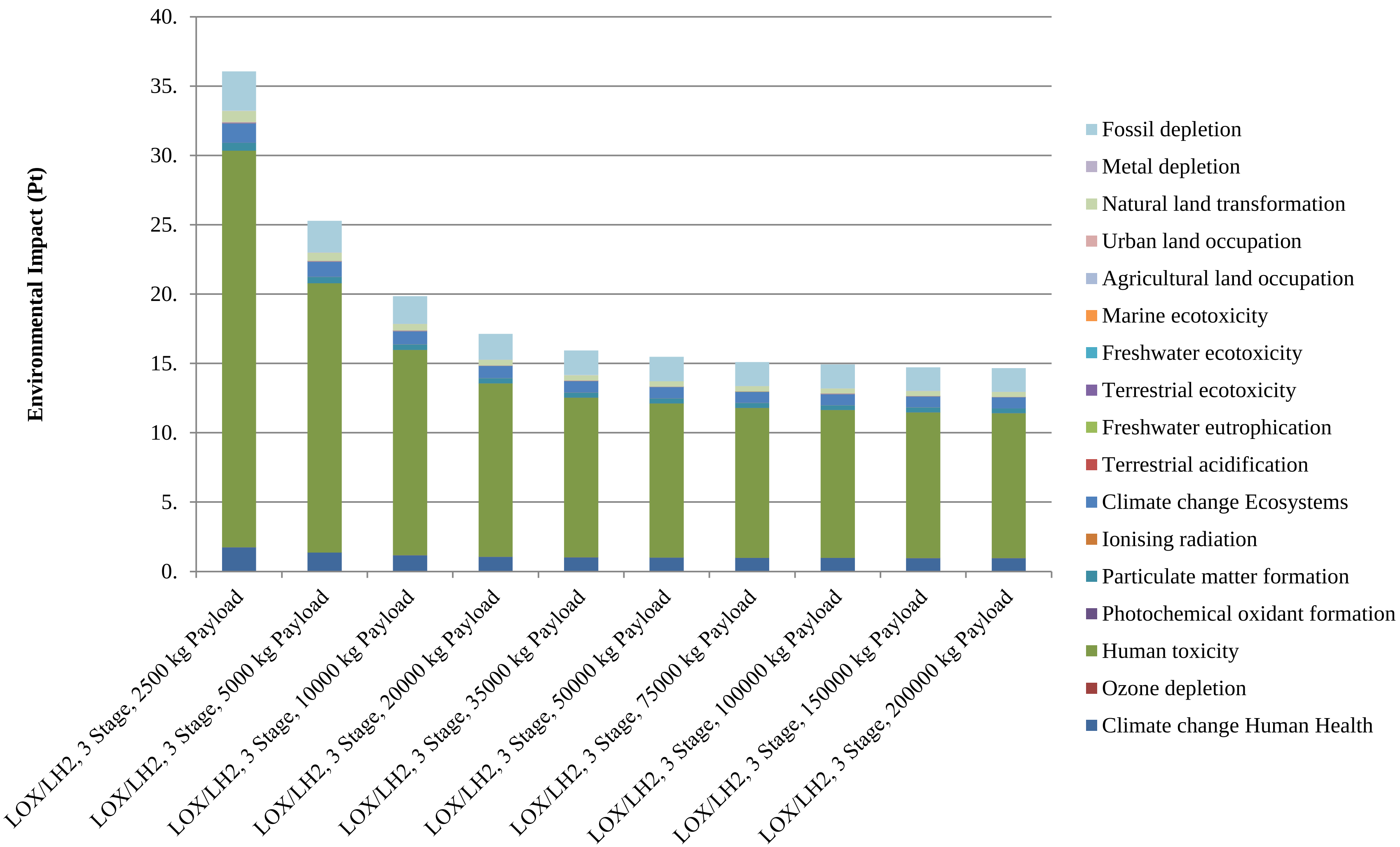


Figure D 3: Comparison of environmental impacts across lift capacities for the baseline three stage, LOX/LH2 rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

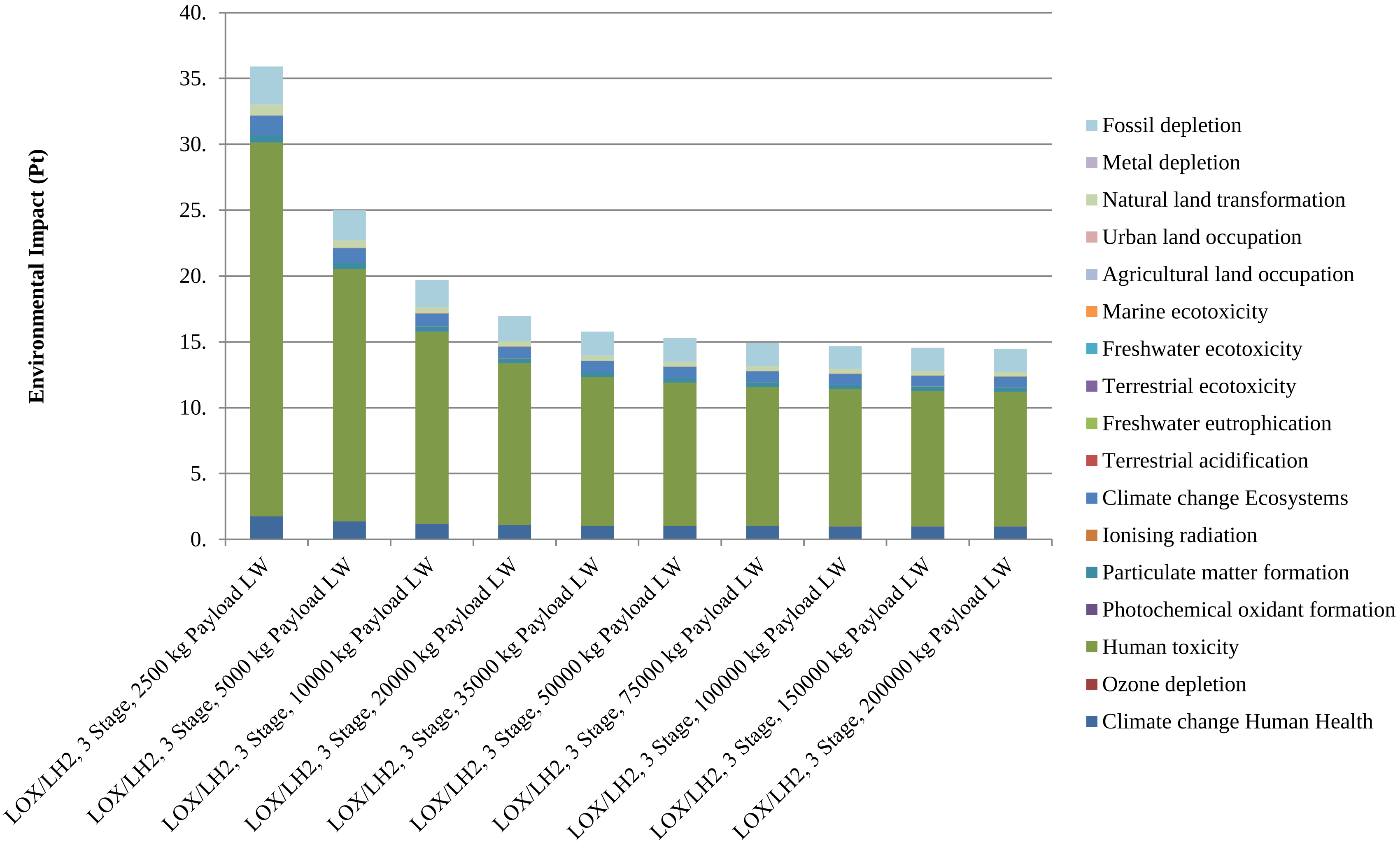


Figure D 4: Comparison of environmental impacts across lift capacities for the light-weighted three stage, LOX/LH2 rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

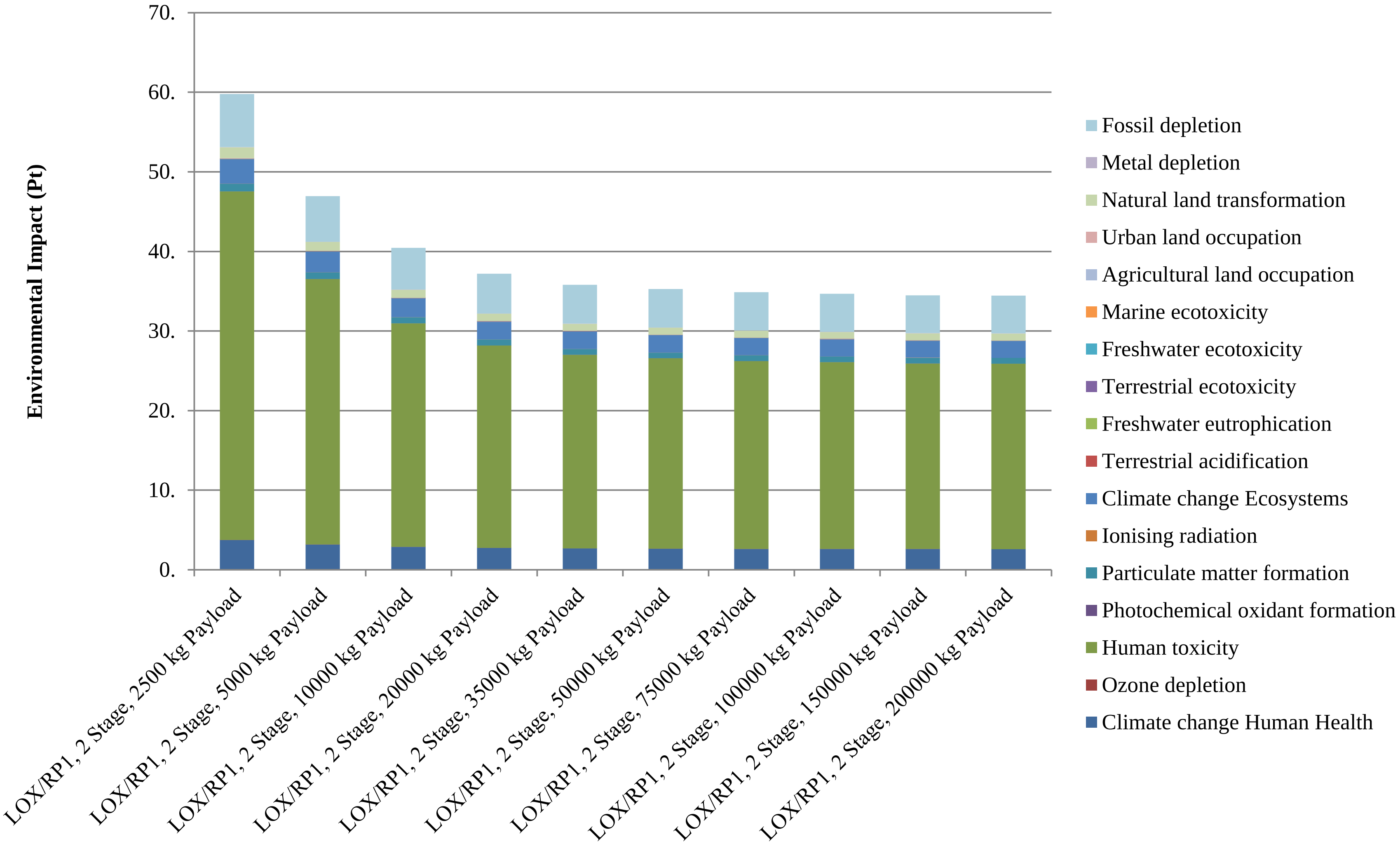


Figure D 5: Comparison of environmental impacts across lift capacities for the baseline two stage, LOX/RP1 rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

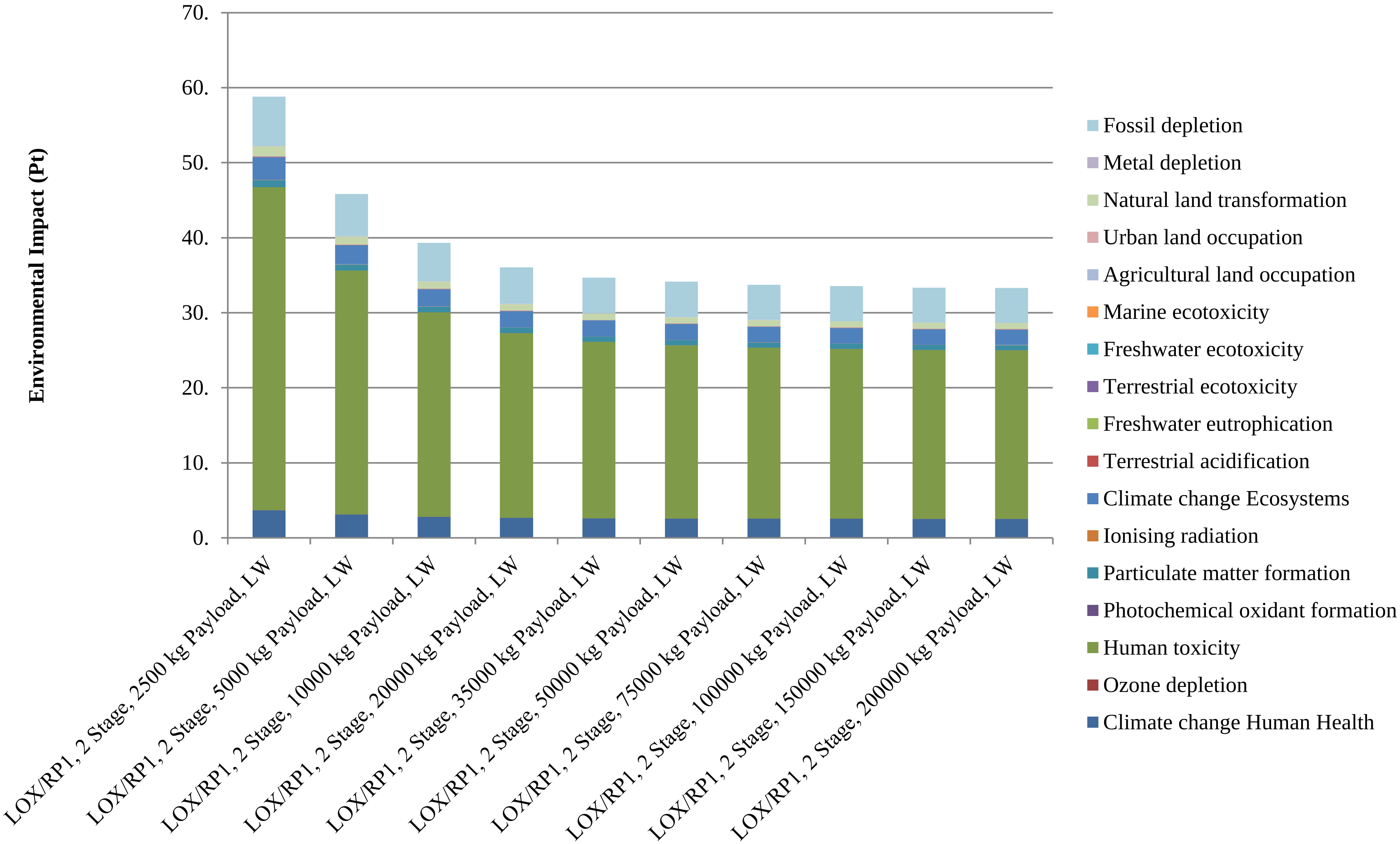


Figure D 6: Comparison of environmental impacts across lift capacities for the light-weighted two stage, LOX/RP1 rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

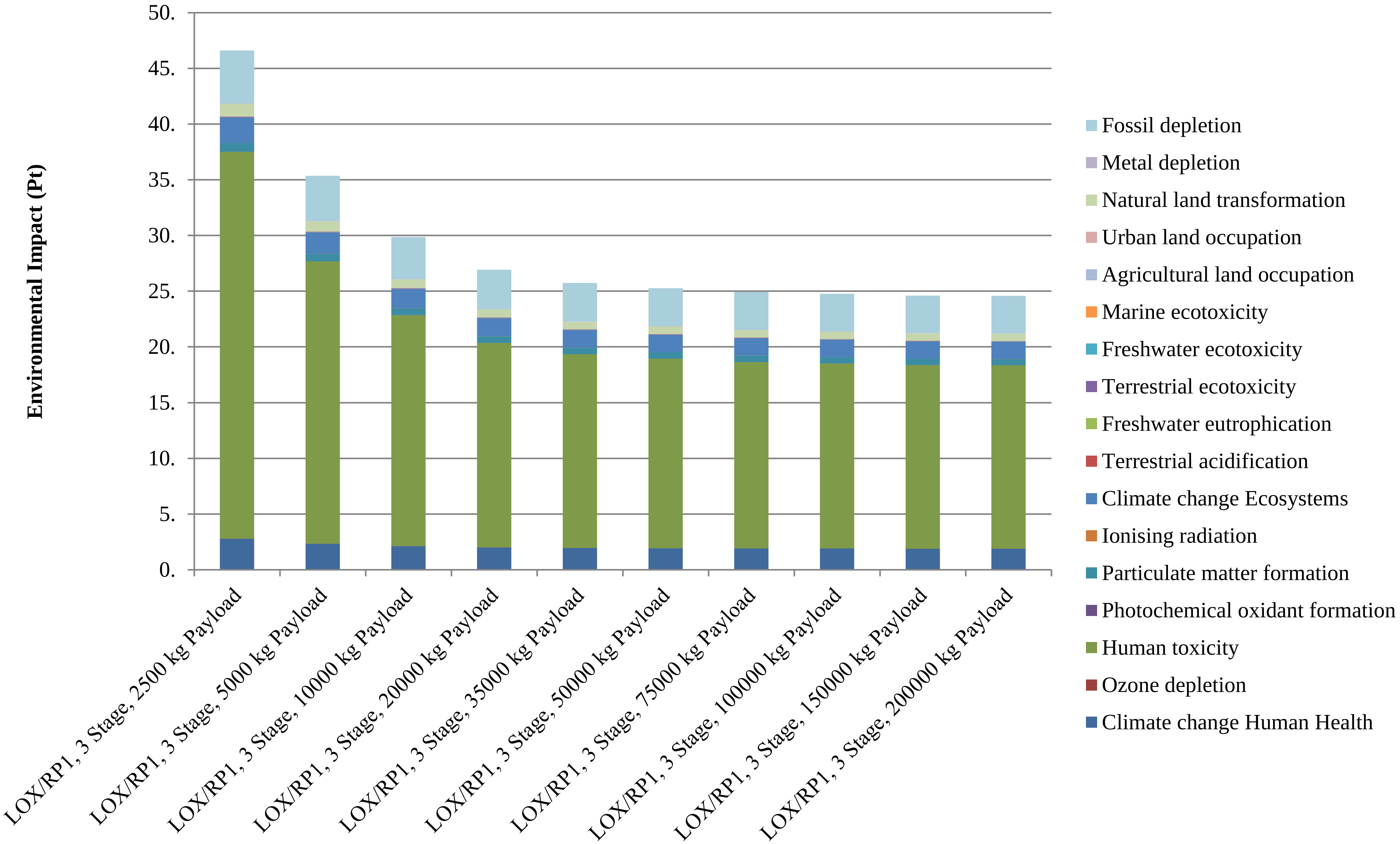


Figure D 7: Comparison of environmental impacts across lift capacities for the baseline three stage, LOX/RP1 rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

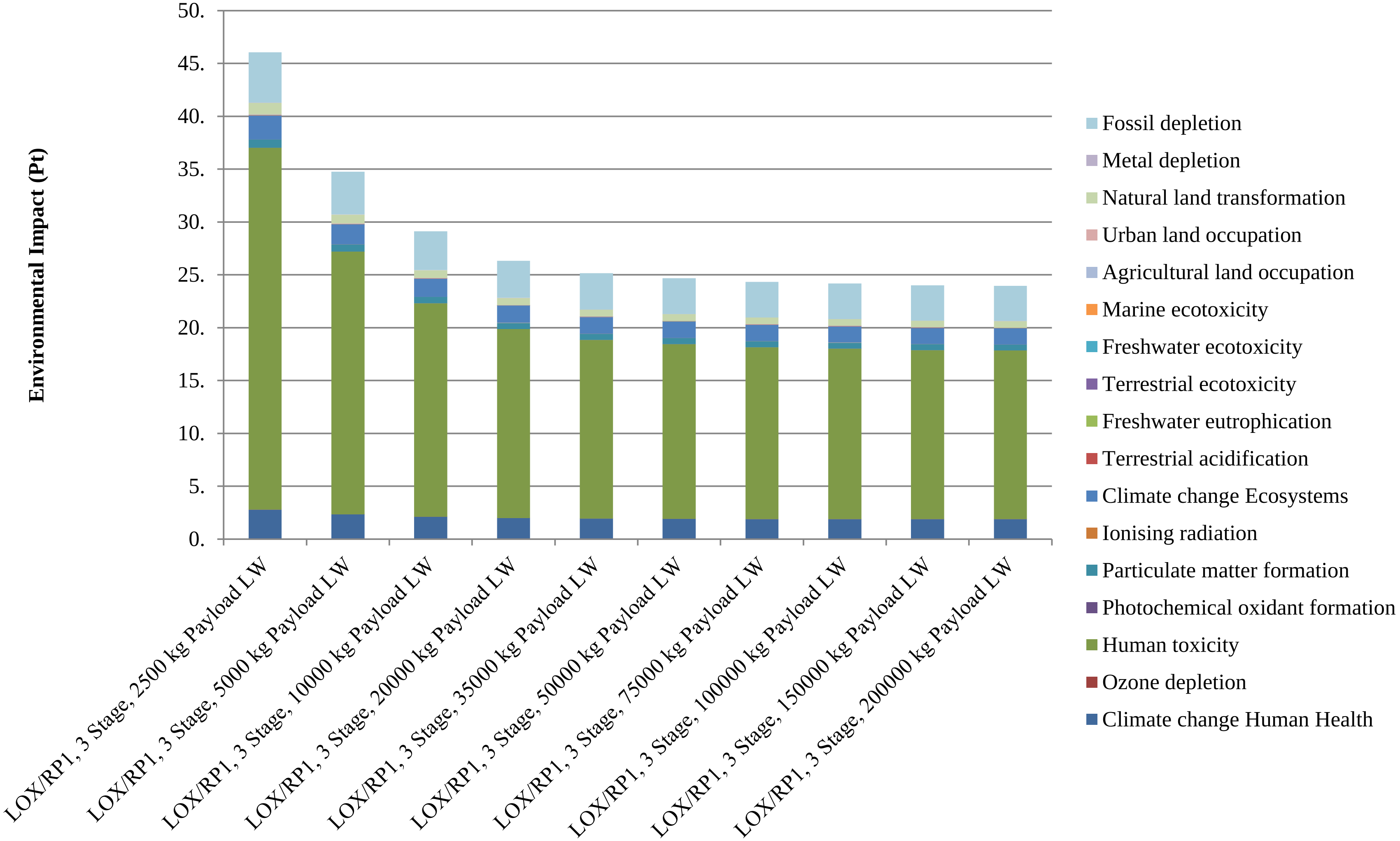


Figure D 8: Comparison of environmental impacts across lift capacities for the light-weighted three stage, LOX/RP1 rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

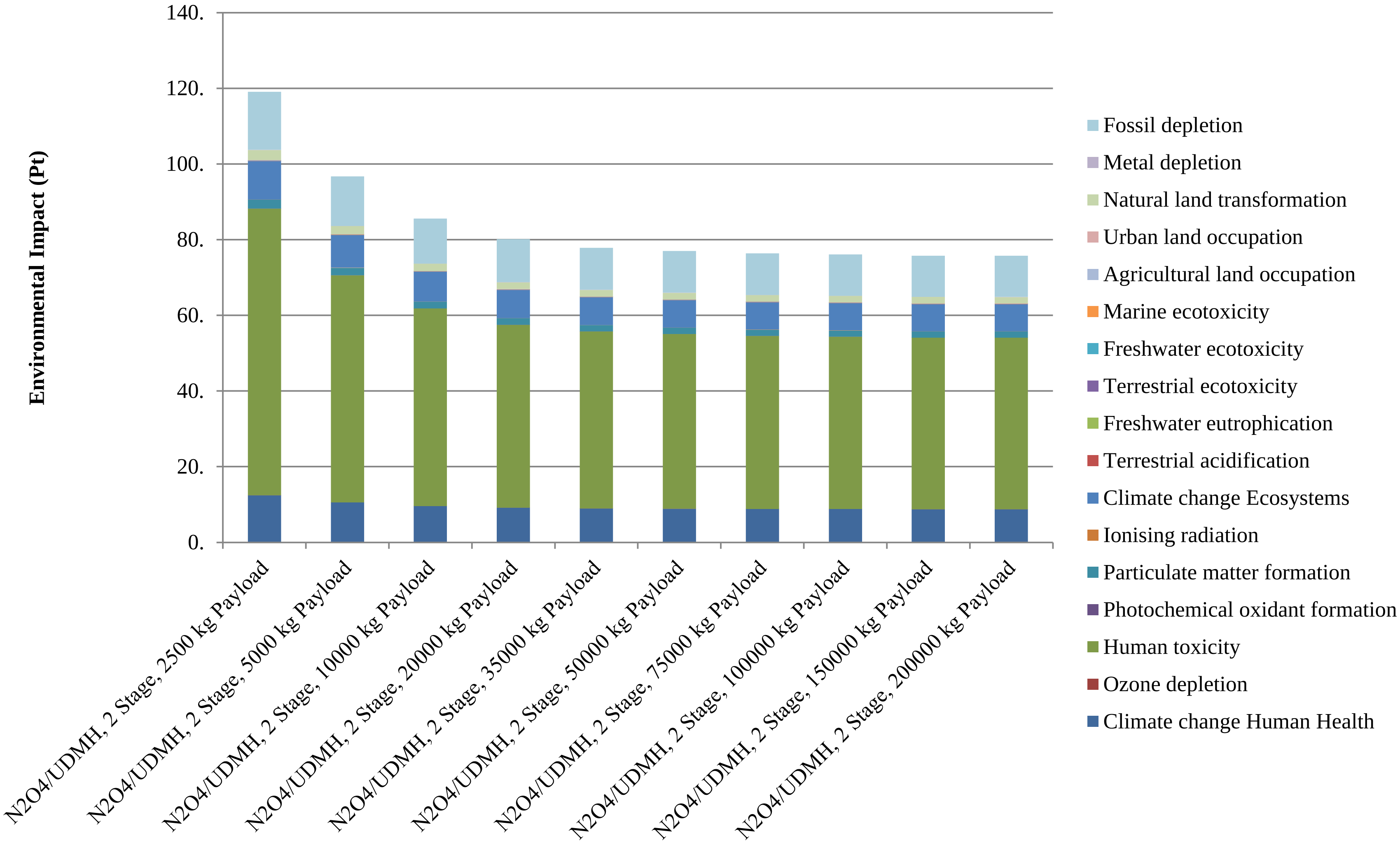


Figure D 9: Comparison of environmental impacts across lift capacities for the baseline two stage, N2O4/UDMH rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

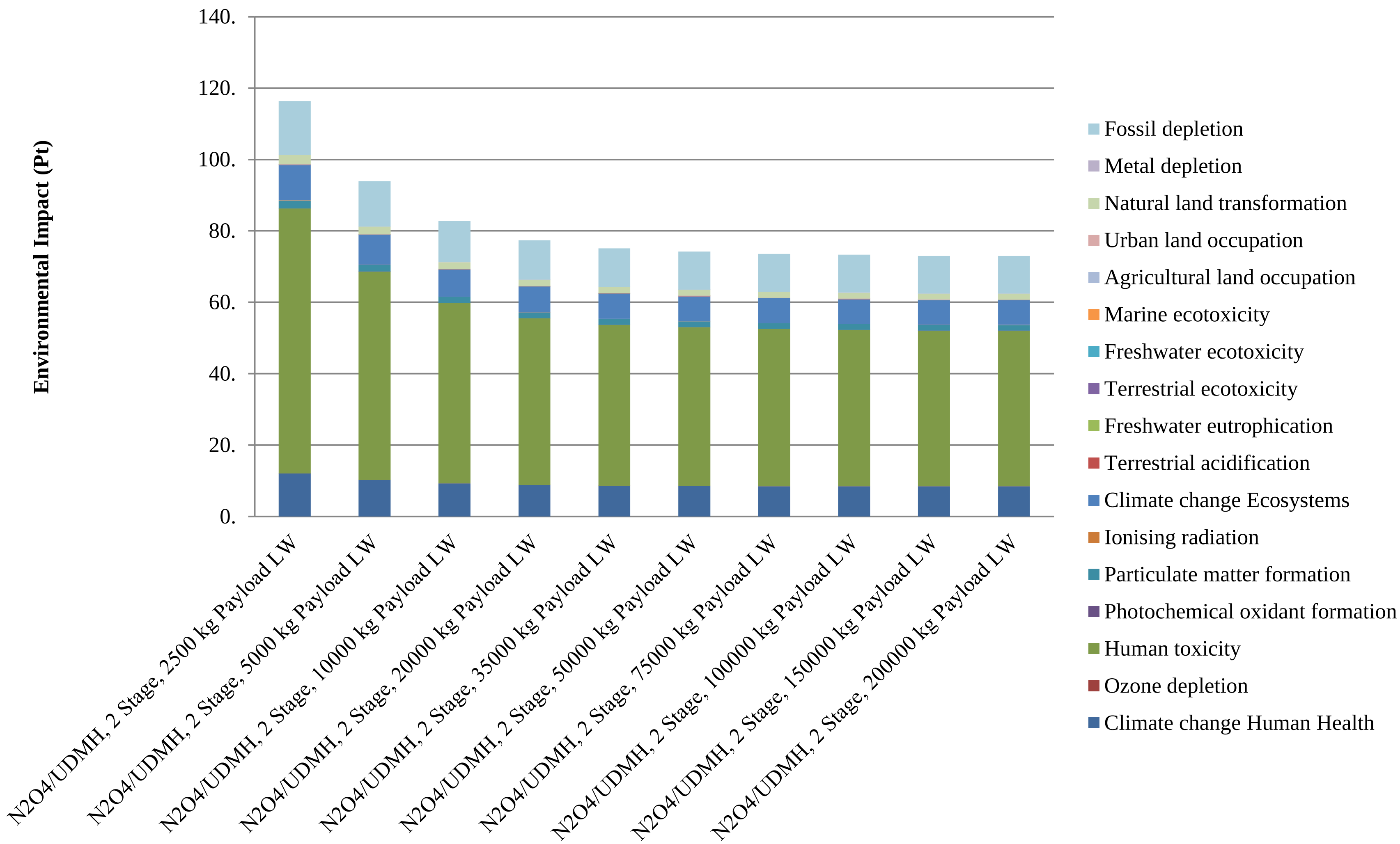


Figure D 10: Comparison of environmental impacts across lift capacities for the light-weighted two stage, N2O4/UDMH rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

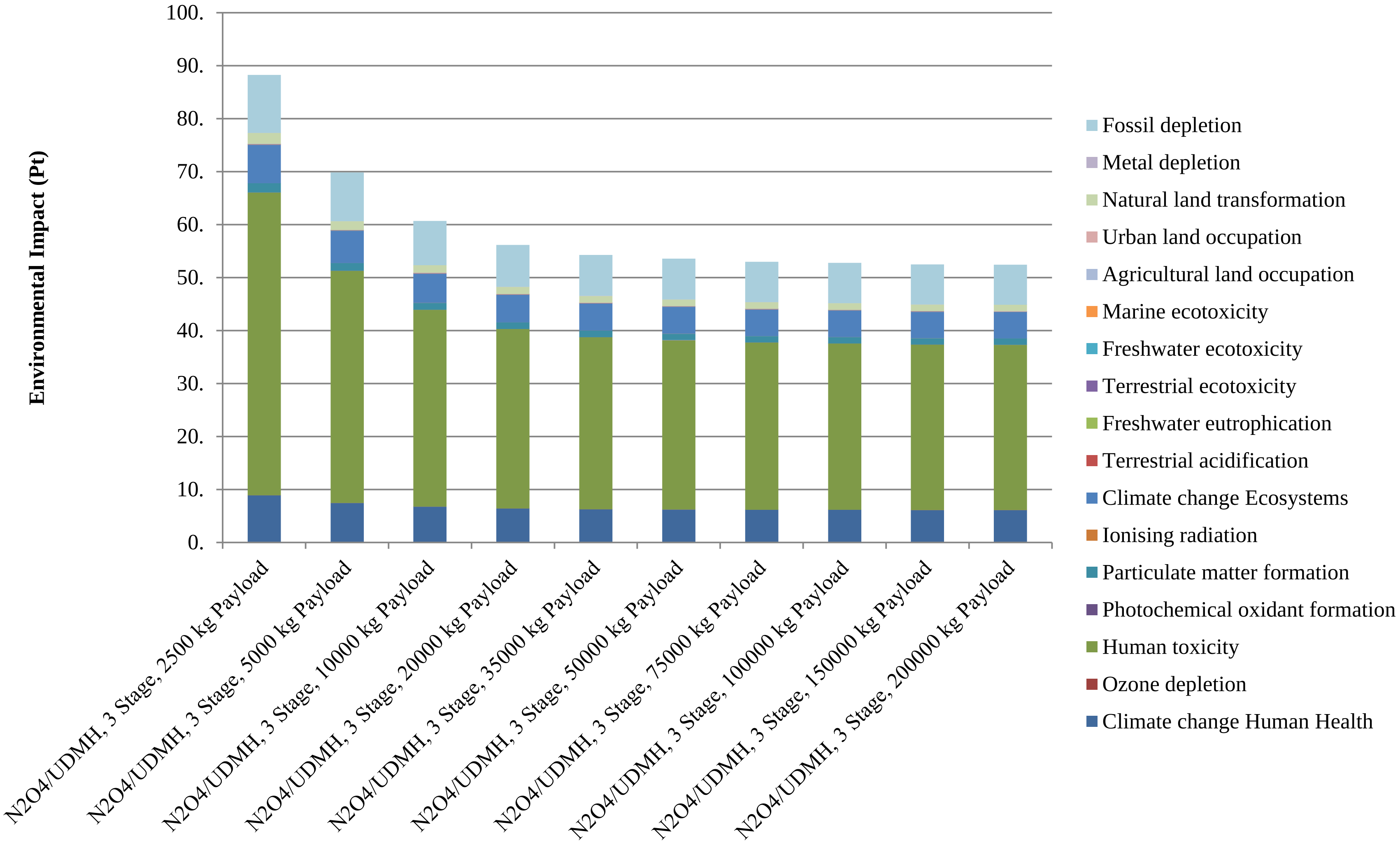


Figure D 11: Comparison of environmental impacts across lift capacities for the baseline three stage, N2O4/UDMH rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

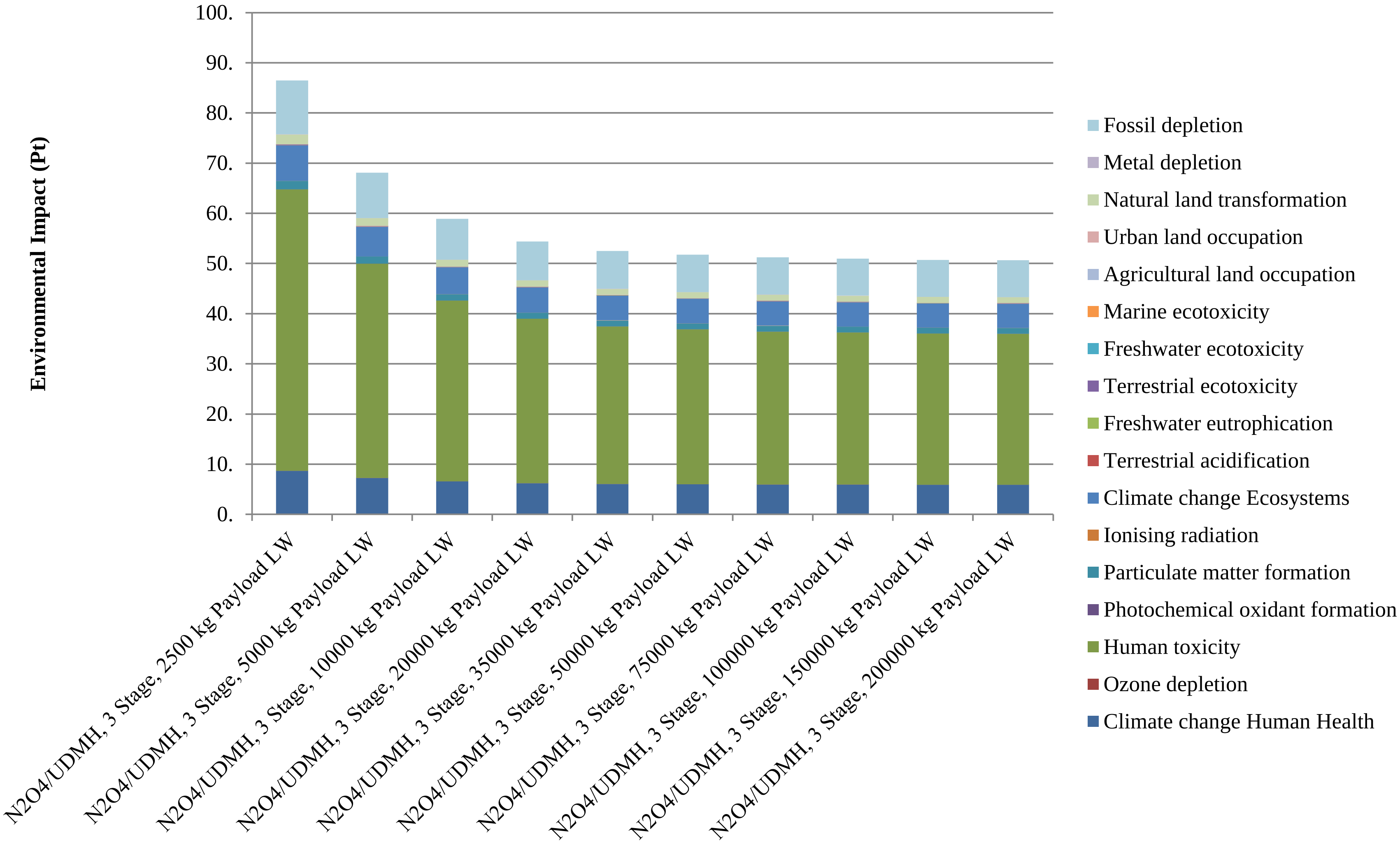


Figure D 12: Comparison of environmental impacts across lift capacities for the light-weighted three stage, N2O4/UDMH rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

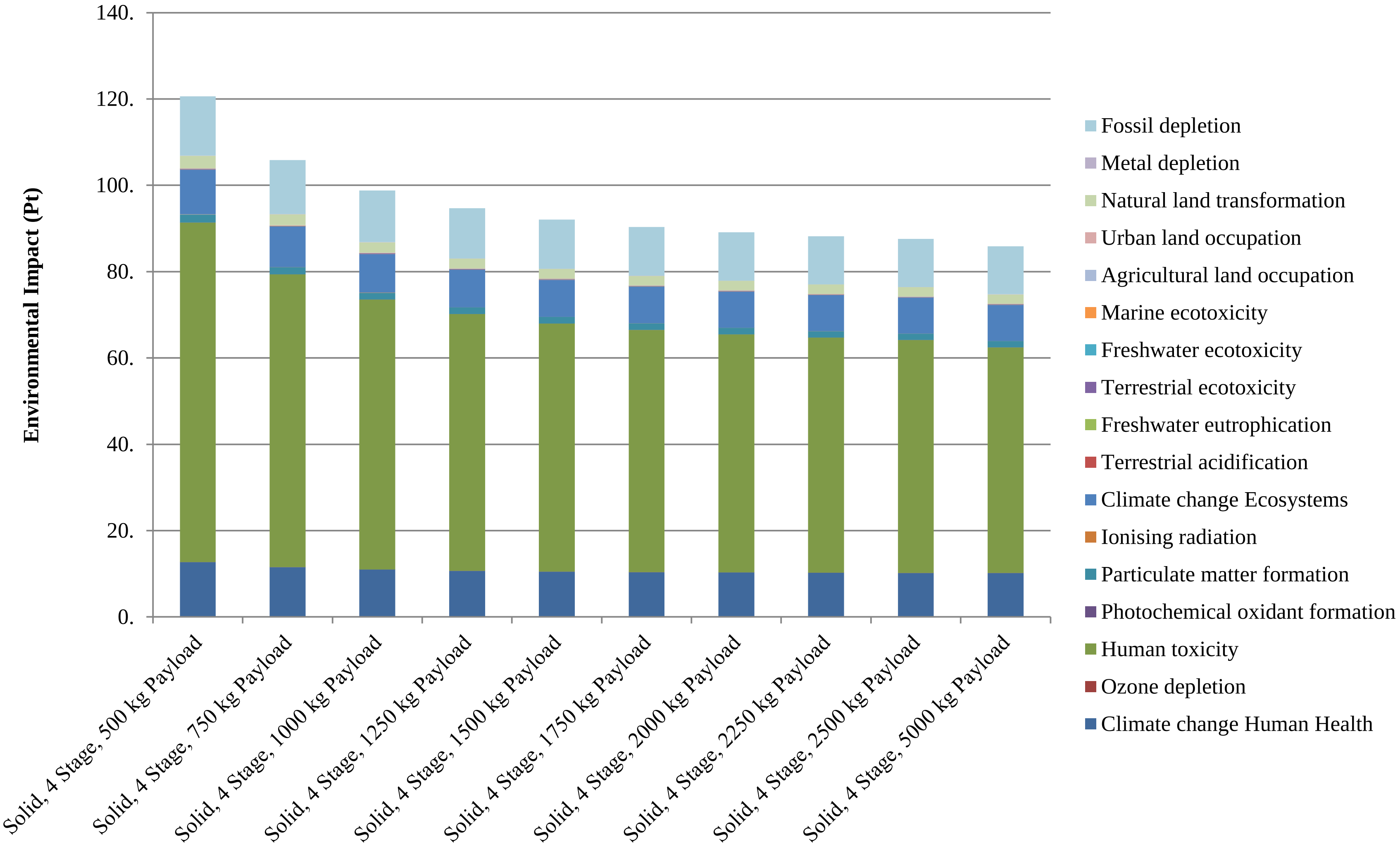


Figure D 13: Comparison of environmental impacts across lift capacities for the baseline four stage, solid rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

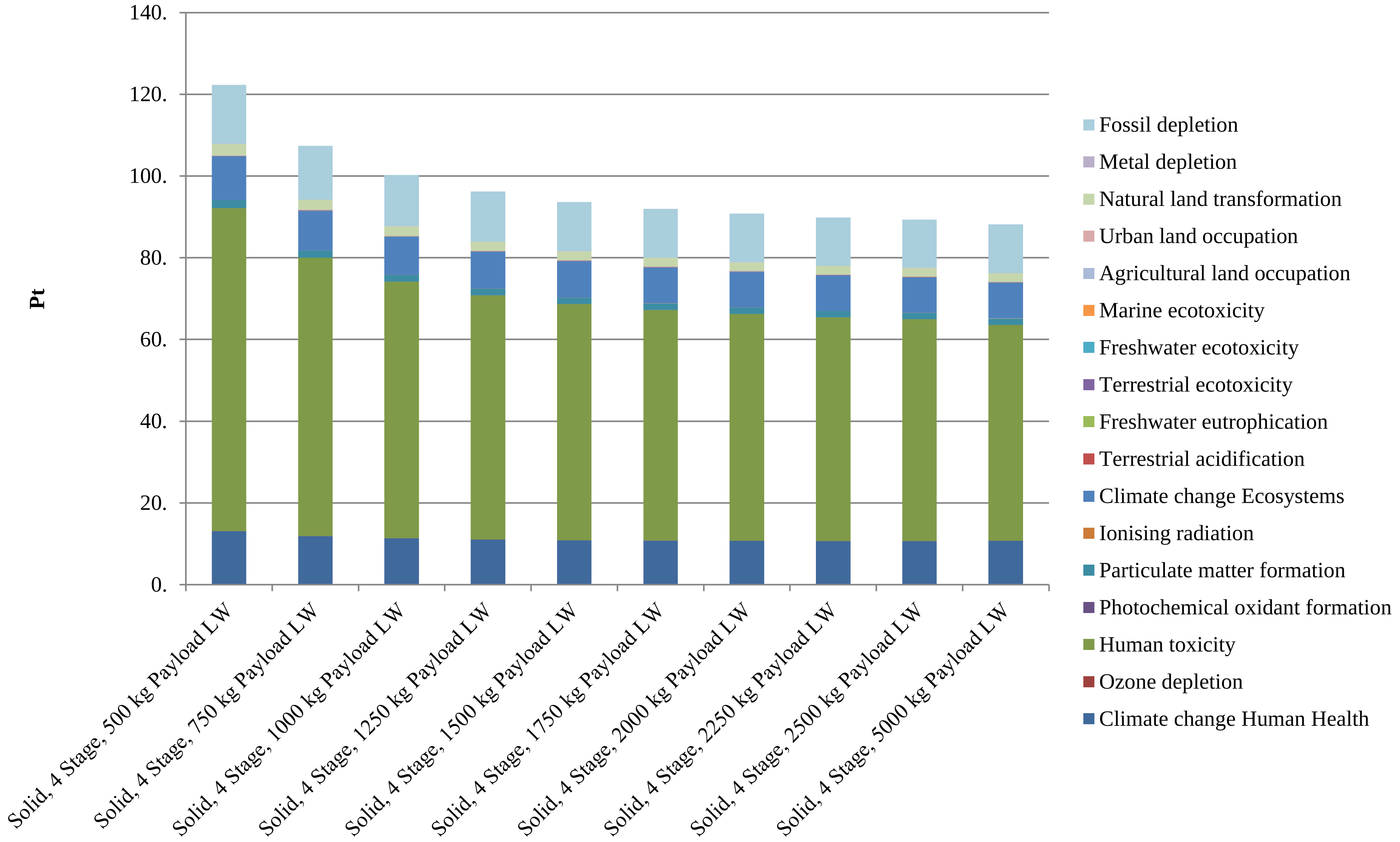


Figure D 14: Comparison of environmental impacts across lift capacities for the solid four stage, solid rockets, normalized for 1 kg payload to LEO, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

APPENDIX E: UNCERTAINTY ANALYSIS RESULTS

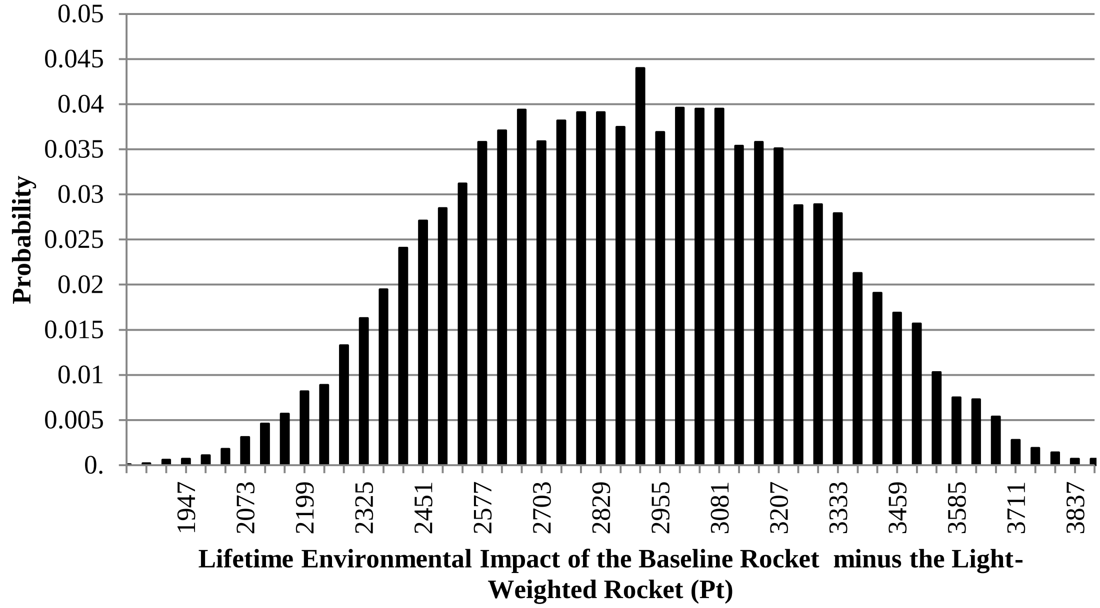


Figure E 1: Probability density function showing the results from the low uncertainty analysis on the two stage, 10,000 kg to LEO, LOX/LH2 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

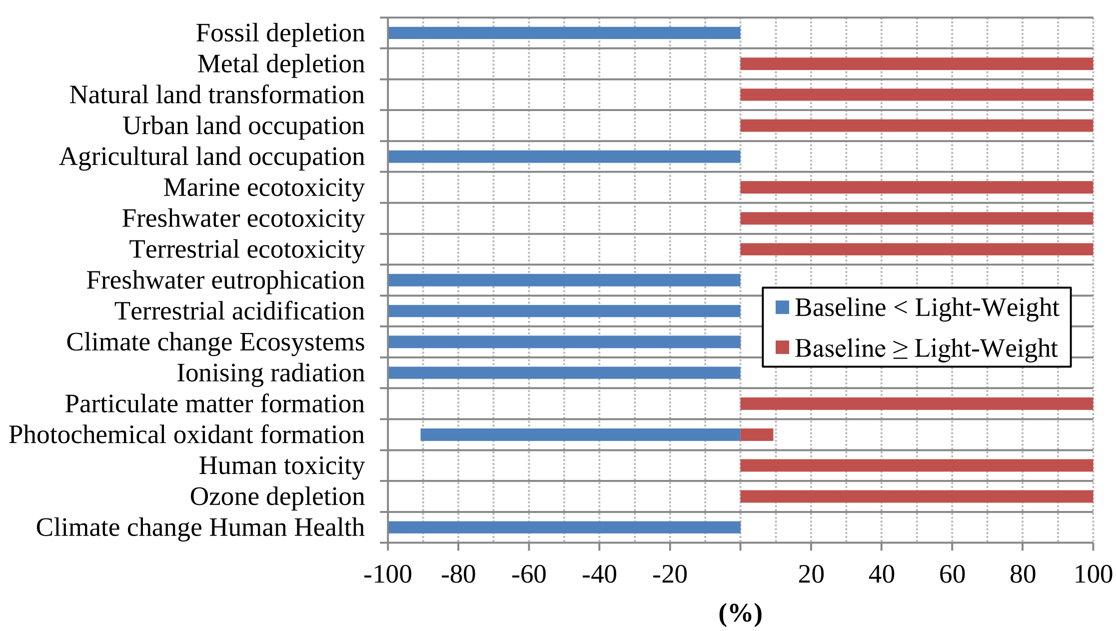


Figure E 2: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, LOX/LH2 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

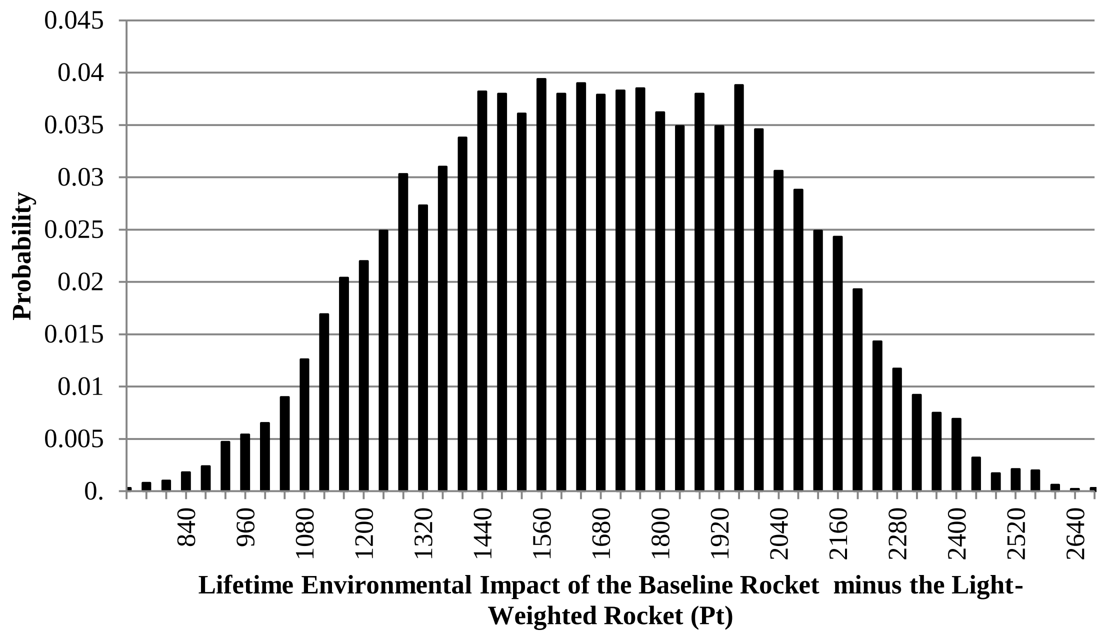


Figure E 3: Probability density function showing the results from the low uncertainty analysis on the three stage, 10,000 kg to LEO, LOX/LH2 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

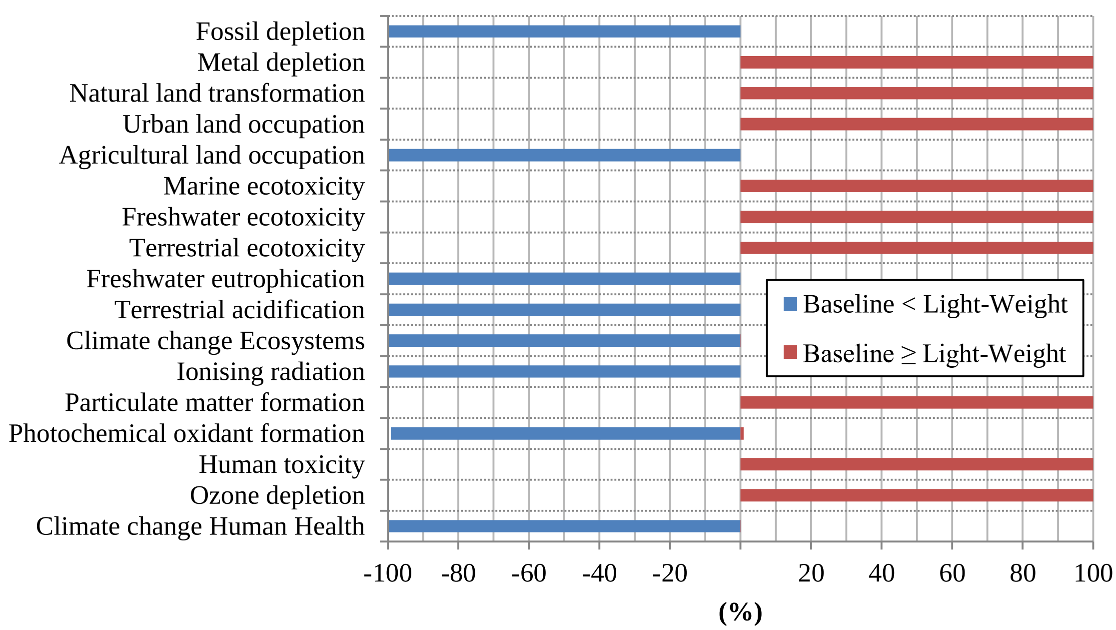


Figure E 4: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the three stage, 10,000 kg to LEO, LOX/LH2 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

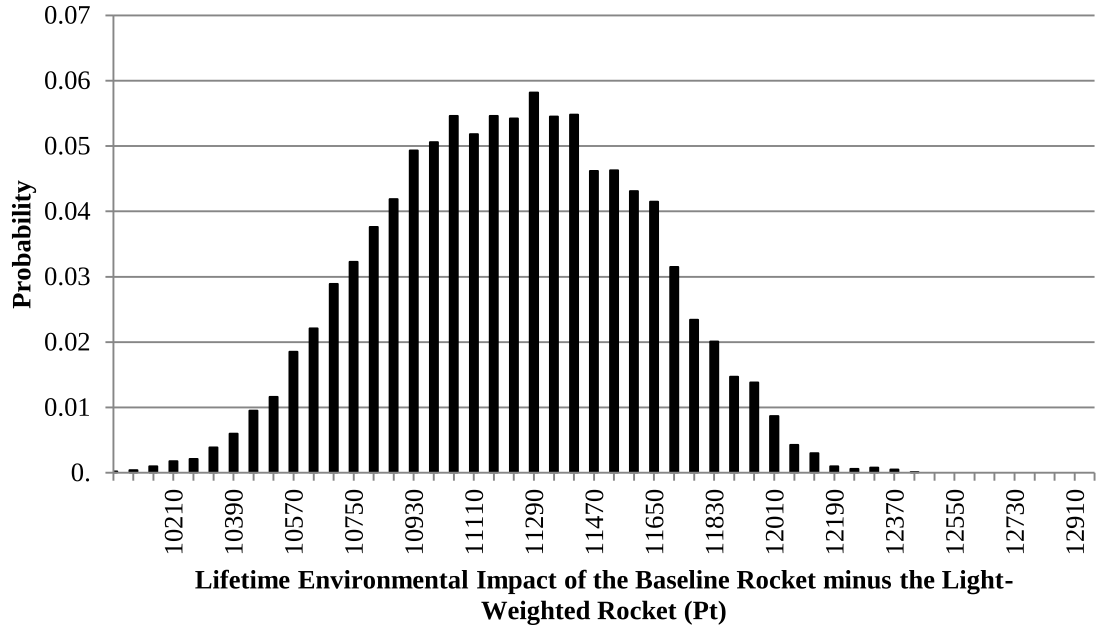


Figure E 5: Probability density function showing the results from the low uncertainty analysis on the two stage, 10,000 kg to LEO, LOX/RP1 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

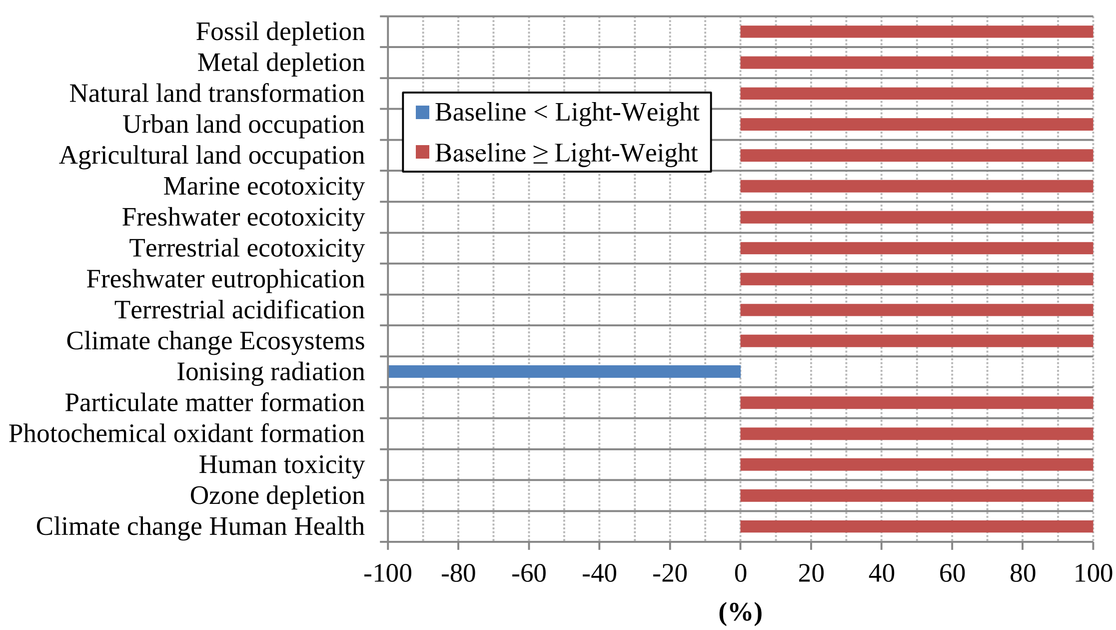


Figure E 6: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, LOX/RP1 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

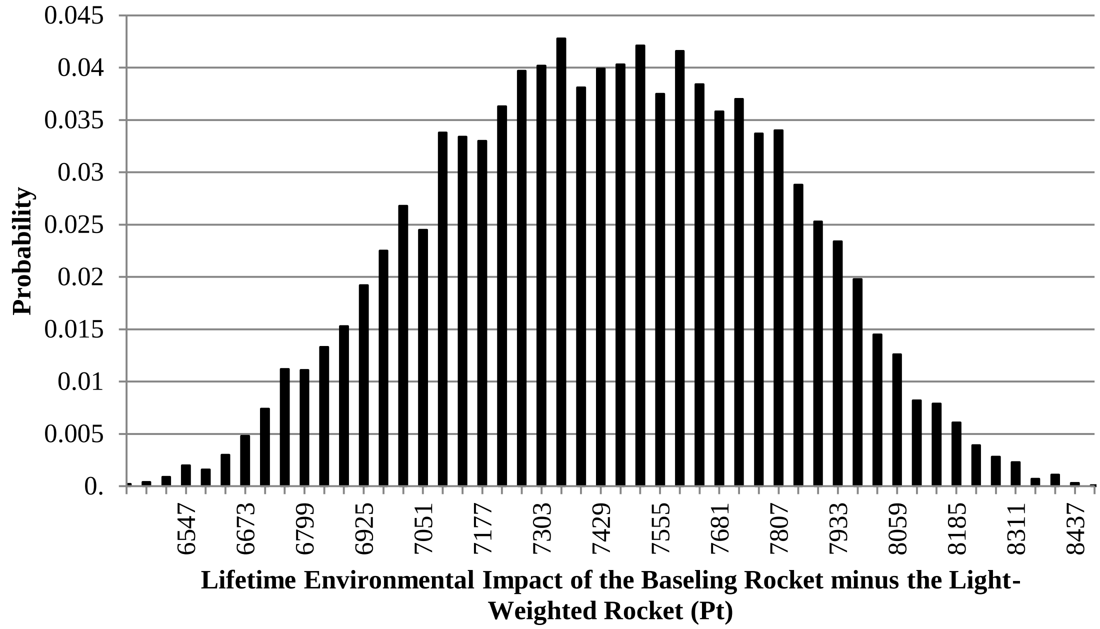


Figure E 7: Probability density function showing the results from the low uncertainty analysis on the three stage, 10,000 kg to LEO, LOX/RP1 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

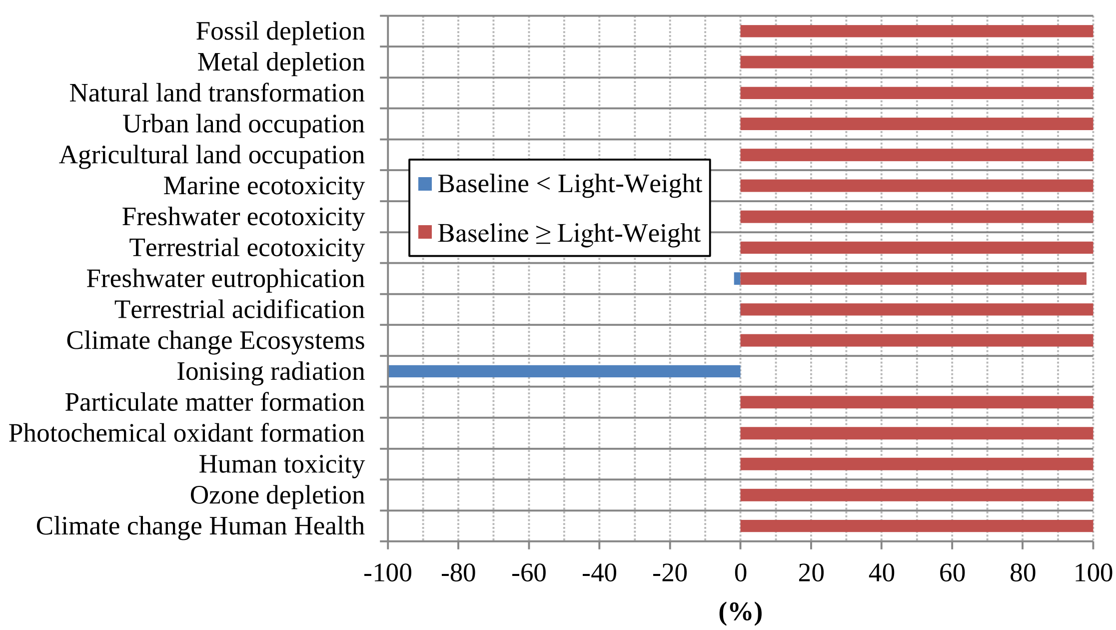


Figure E 8: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the three stage, 10,000 kg to LEO, LOX/RP1 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

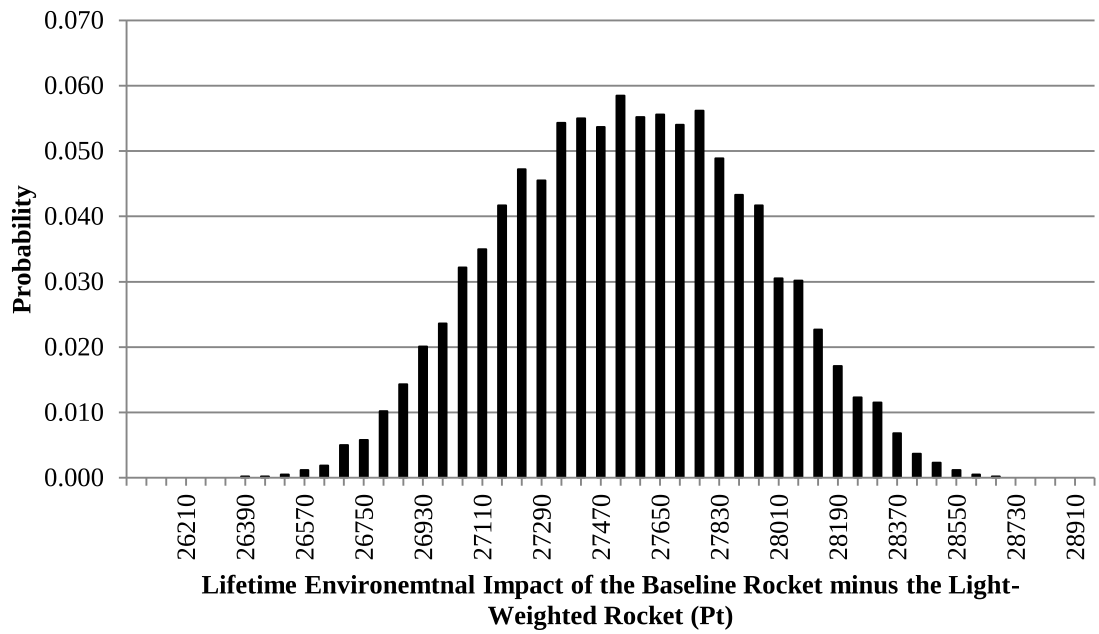


Figure E 9: Probability density function showing the results from the low uncertainty analysis on the two stage, 10,000 kg to LEO, N2O4/UDMH Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

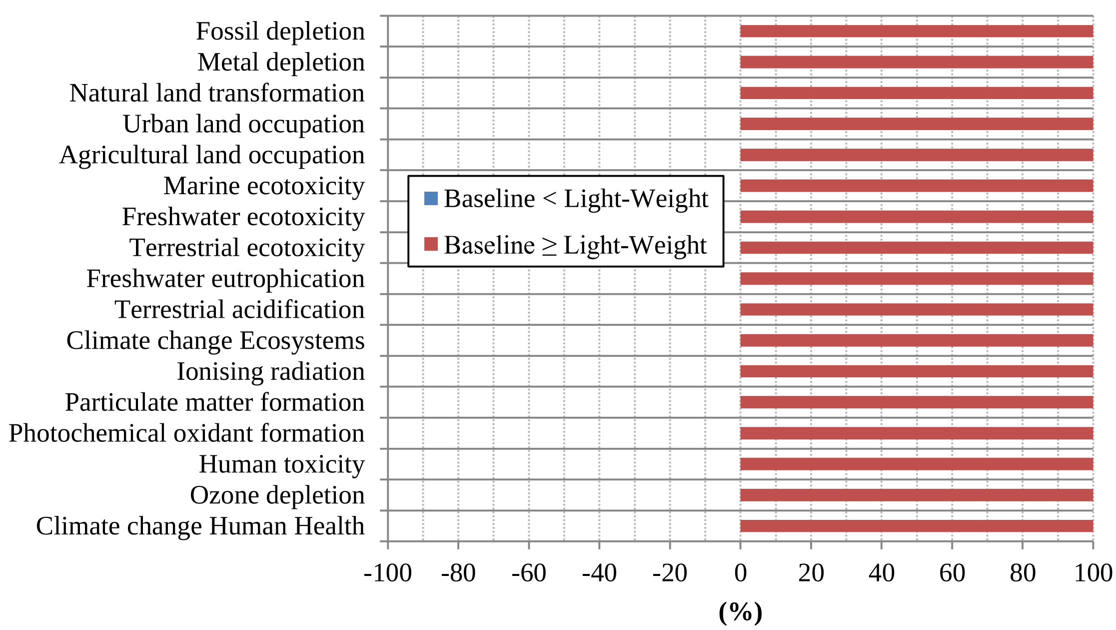


Figure E 10: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, N2O4/UDMH rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

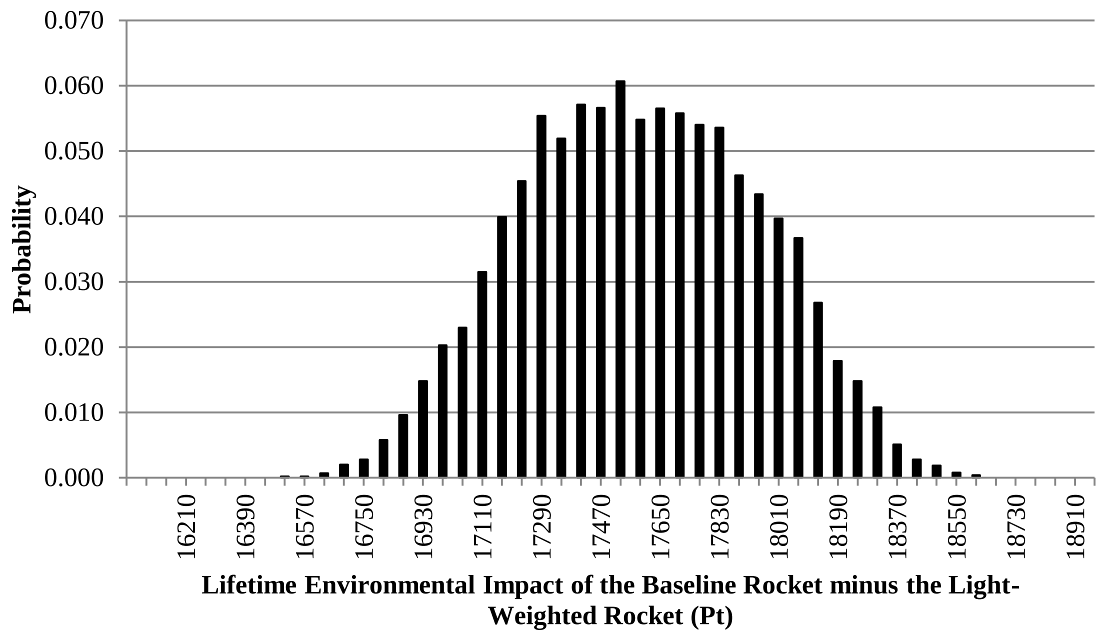


Figure E 11: Probability density function showing the results from the low uncertainty analysis on the three stage, 10,000 kg to LEO, N2O4/UDMH Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

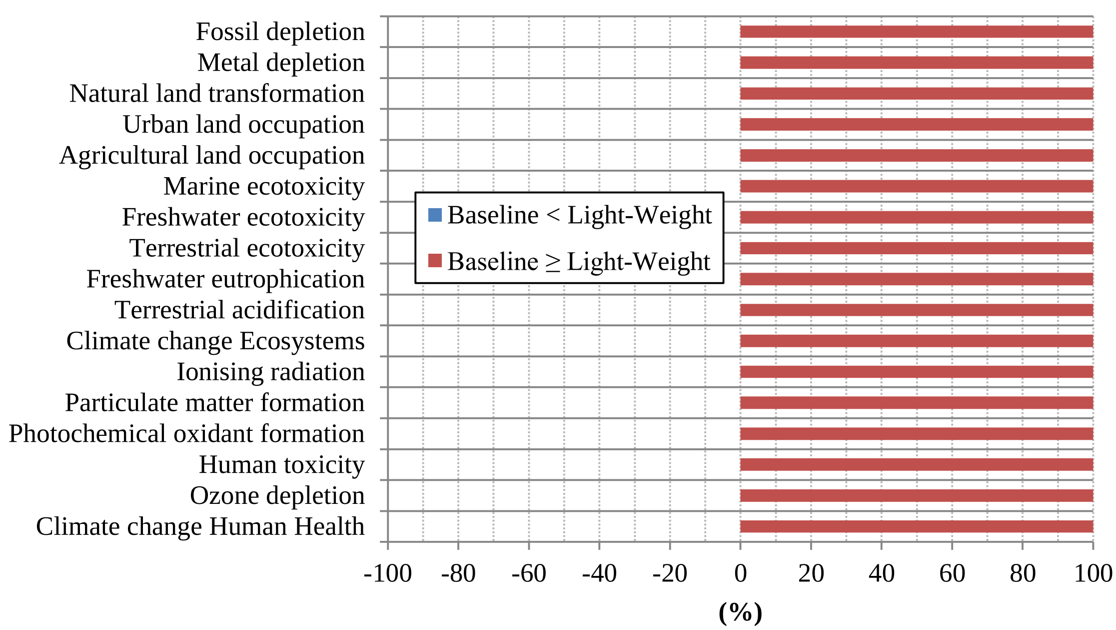


Figure E 12: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the three stage, 10,000 kg to LEO, N2O4/UDMH rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

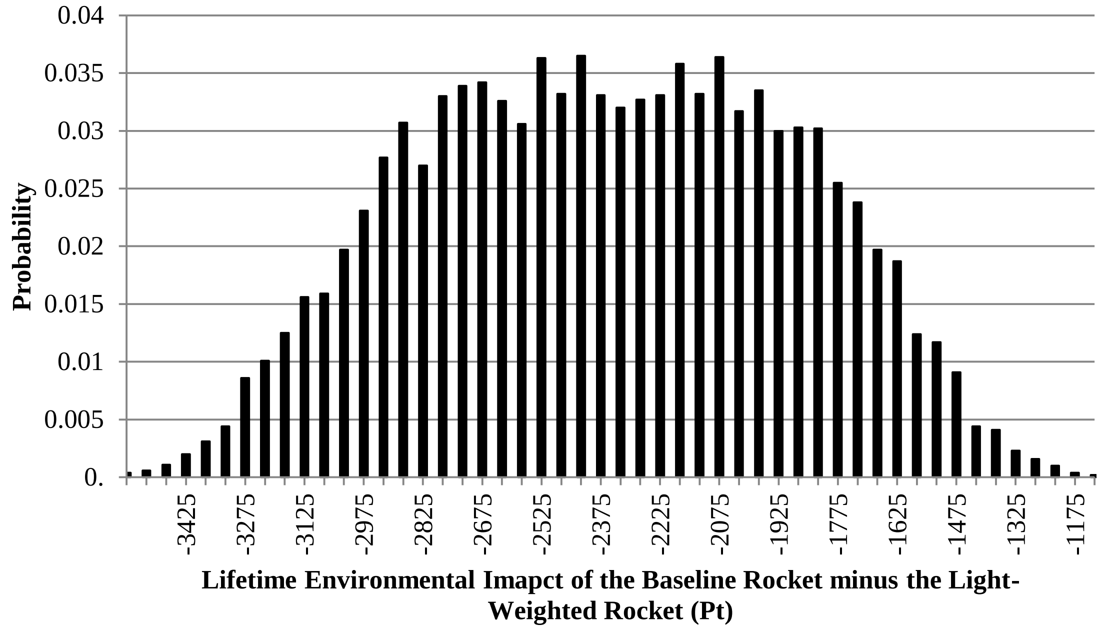


Figure E 13: Probability density function showing the results from the low uncertainty analysis on the four stage, 1,500 kg to LEO, Solid Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

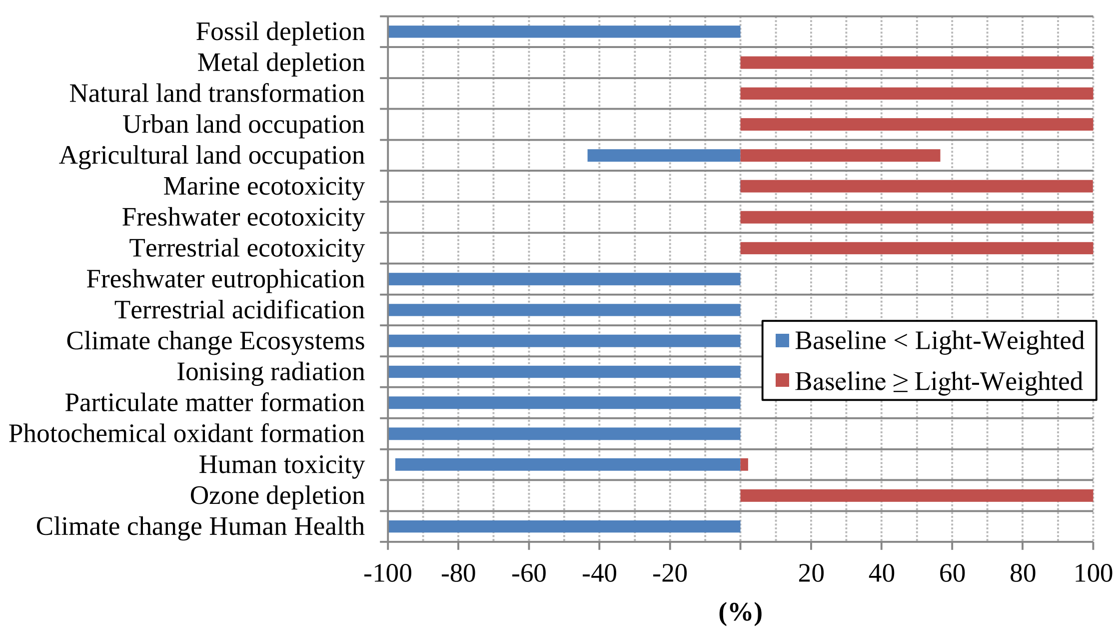


Figure E 14: Categories for which light-weighting was an improvement during the low uncertainty analysis, and the likelihood of this occurrence for the four stage, 1,500 kg to LEO, solid rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

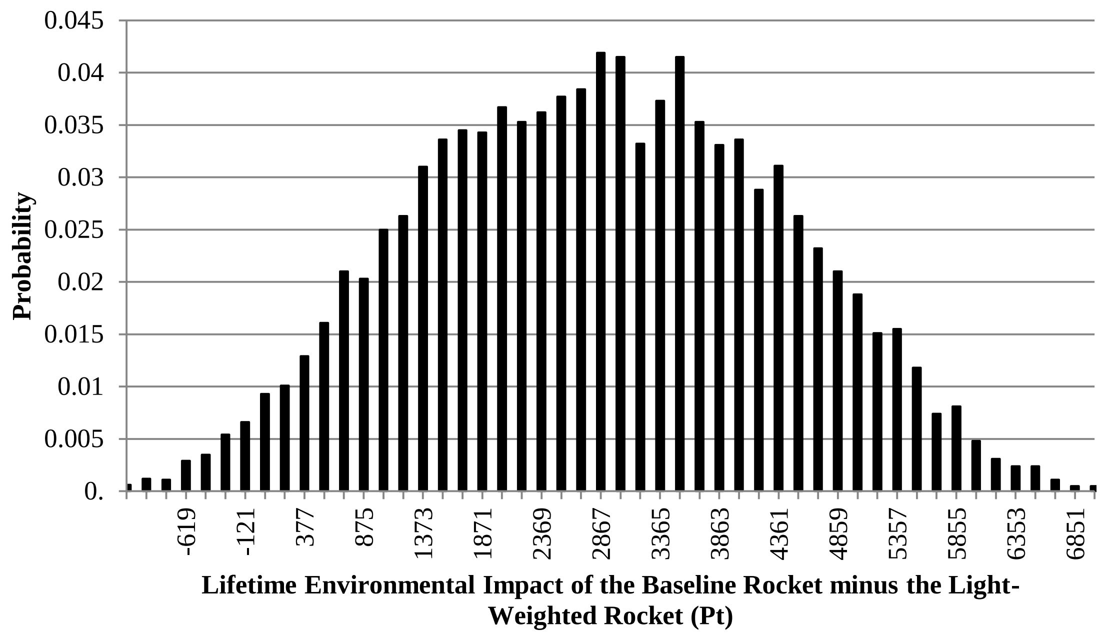


Figure E 15: Probability density function showing the results from the moderate uncertainty analysis on the two stage, 10,000 kg to LEO, LOX/LH2 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

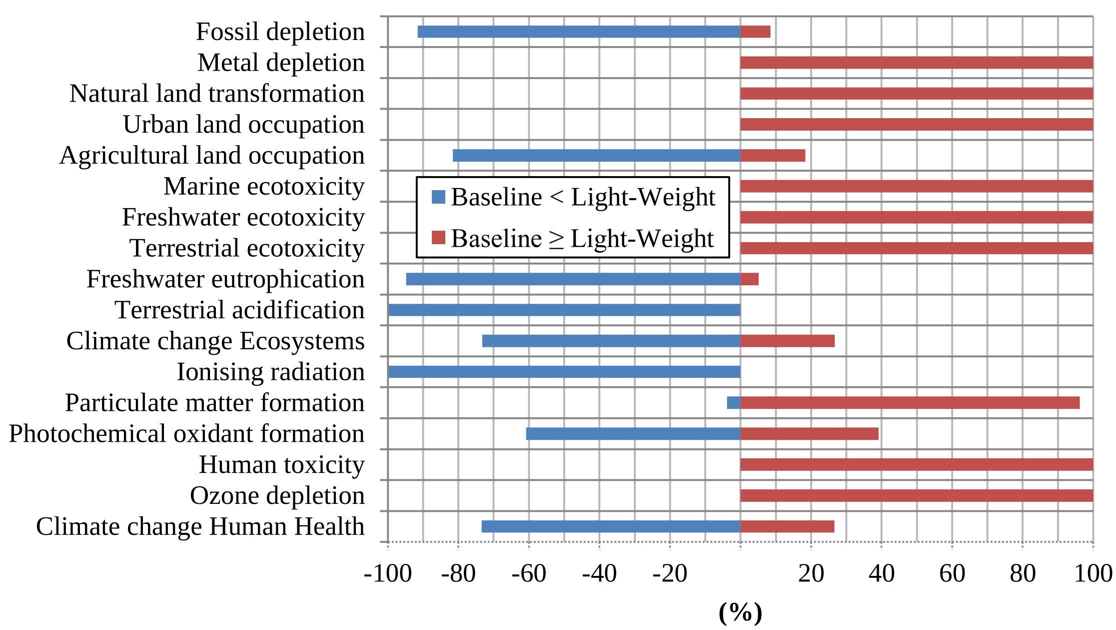


Figure E 16: Categories for which light-weighting was an improvement during the moderate uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, LOX/LH2 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

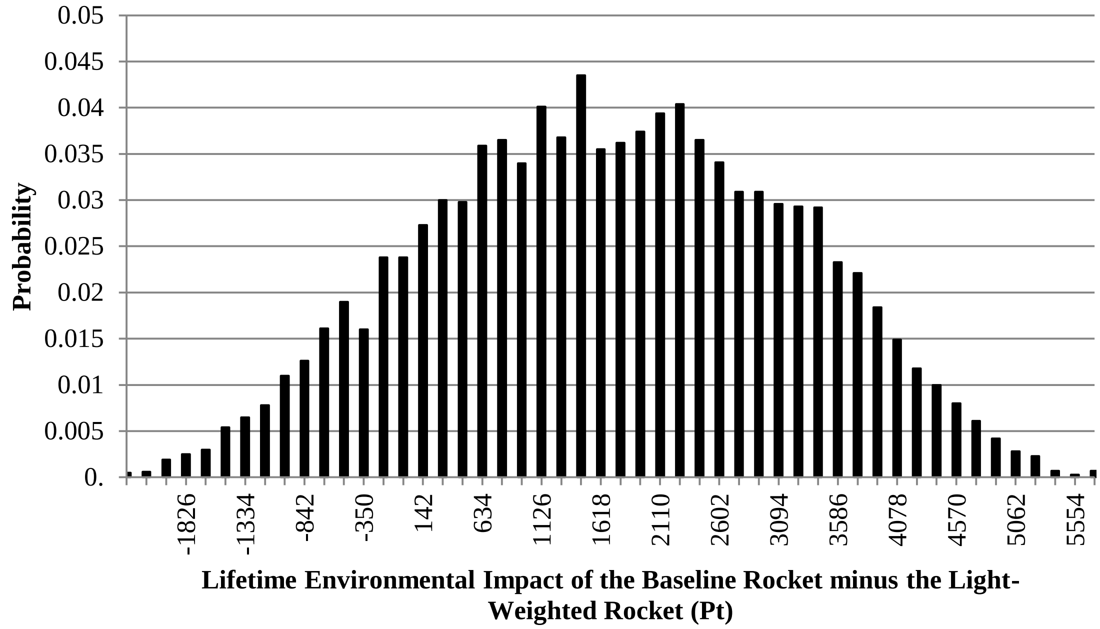


Figure E 17: Probability density function showing the results from the moderate uncertainty analysis on the three stage, 10,000 kg to LEO, LOX/LH2 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

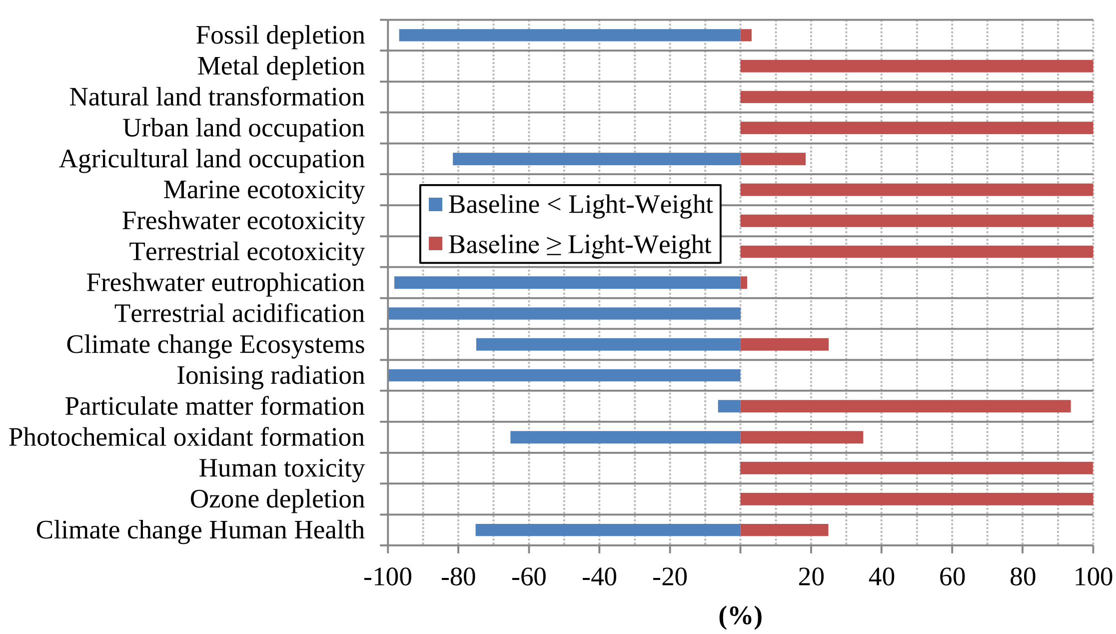


Figure E 18: Categories for which light-weighting was an improvement during the moderate uncertainty analysis, and the likelihood of this occurrence for the three stage, 10,000 kg to LEO, LOX/LH2 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

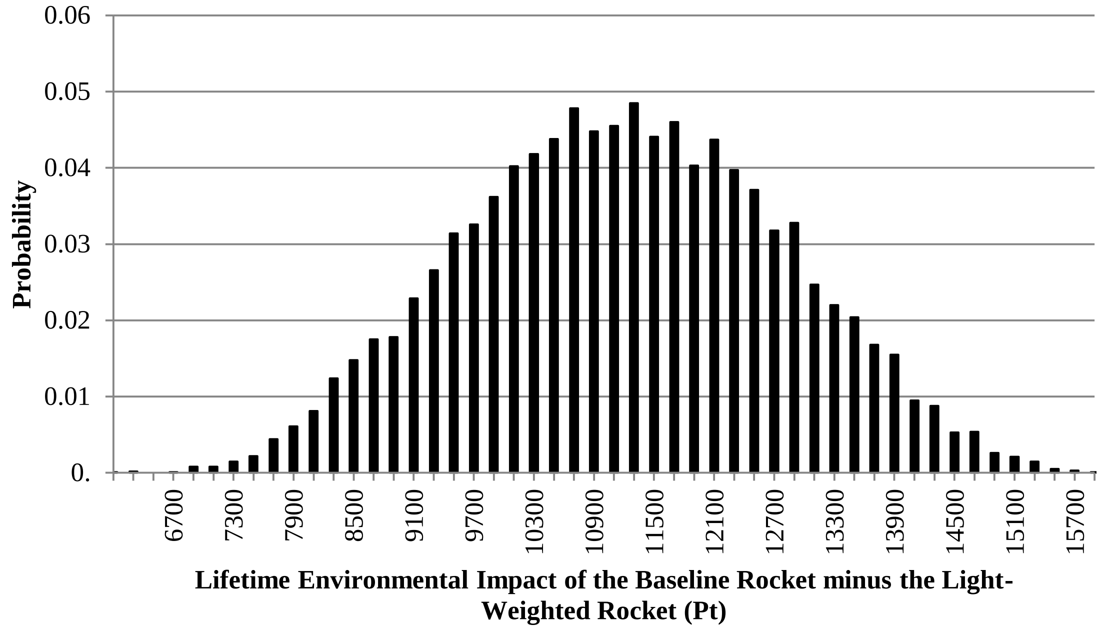


Figure E 19: Probability density function showing the results from the moderate uncertainty analysis on the two stage, 10,000 kg to LEO, LOX/RP1 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

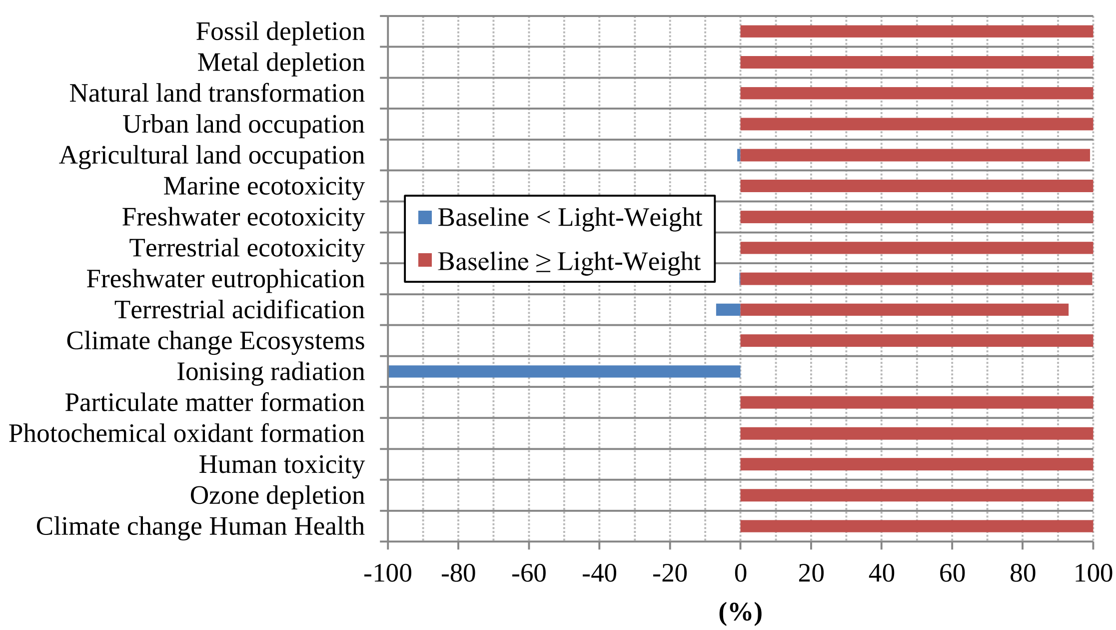


Figure E 20: Categories for which light-weighting was an improvement during the moderate uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, LOX/RP1 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

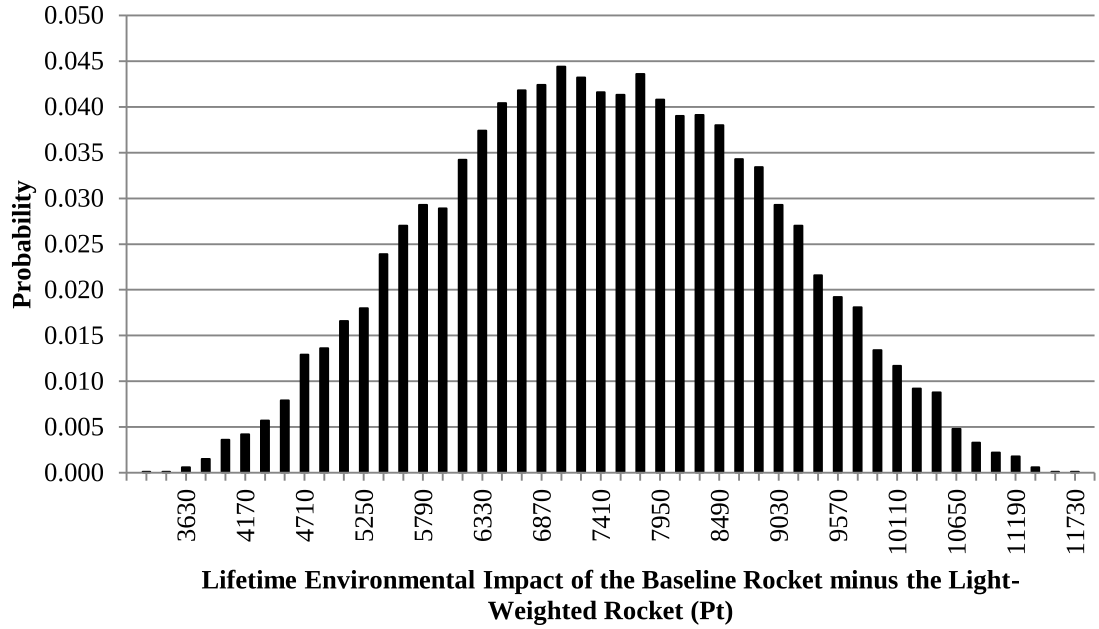


Figure E 21: Probability density function showing the results from the moderate uncertainty analysis on the three stage, 10,000 kg to LEO, LOX/RP1 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

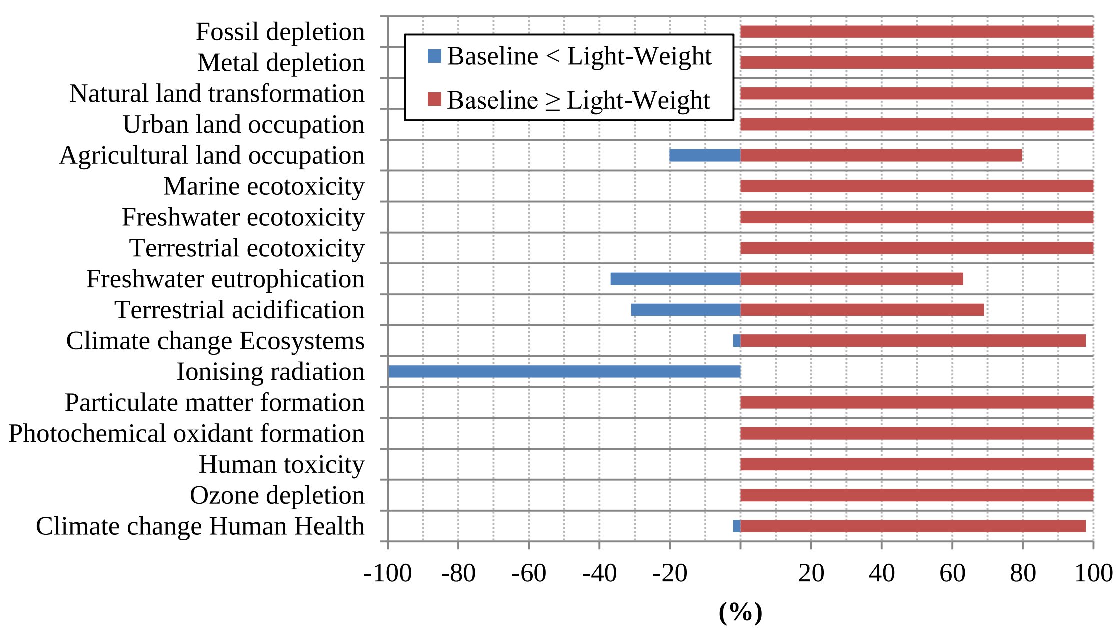


Figure E 22: Categories for which light-weighting was an improvement during the moderate uncertainty analysis, and the likelihood of this occurrence for the three stage, 10,000 kg to LEO, LOX/RP1 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

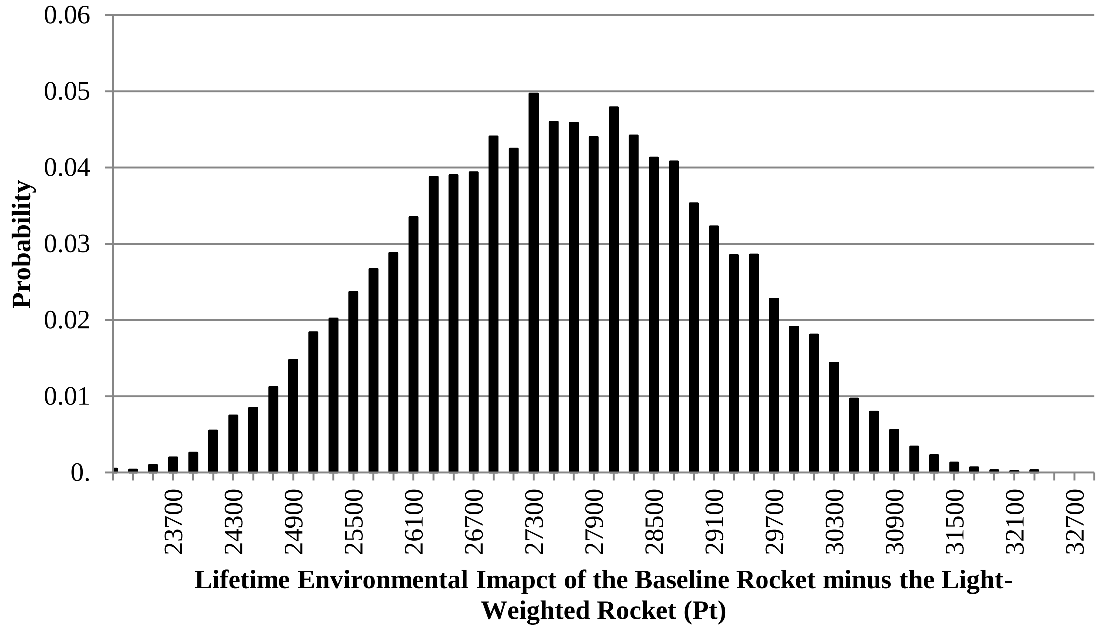


Figure E 23: Probability density function showing the results from the moderate uncertainty analysis on the two stage, 10,000 kg to LEO, N2O4/UDMH Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

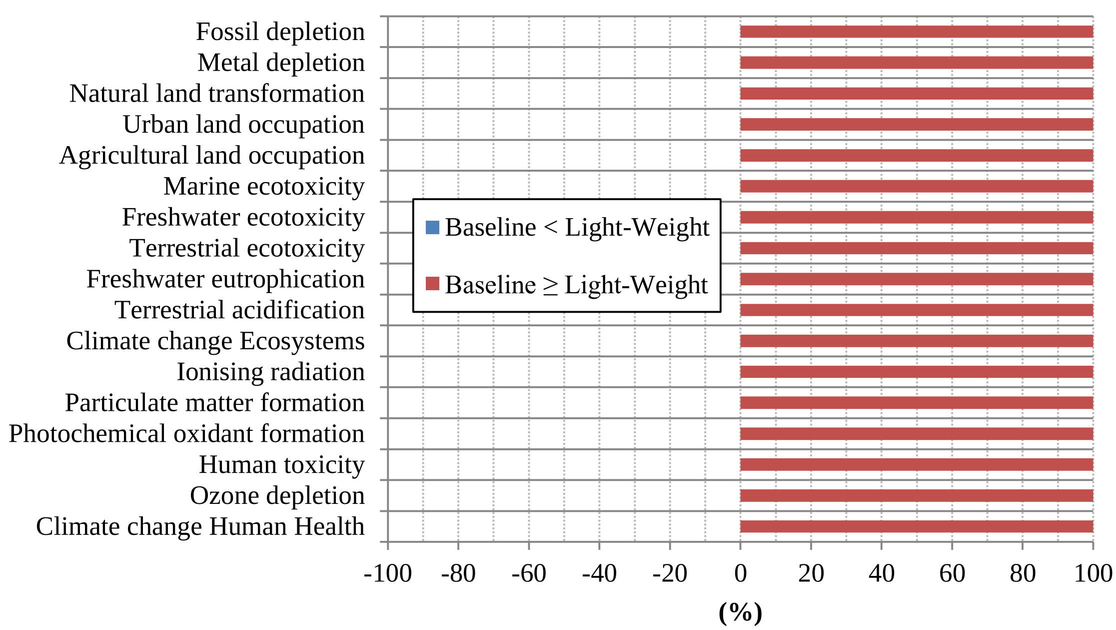


Figure E 24: Categories for which light-weighting was an improvement during the moderate uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, N2O4/UDMH rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

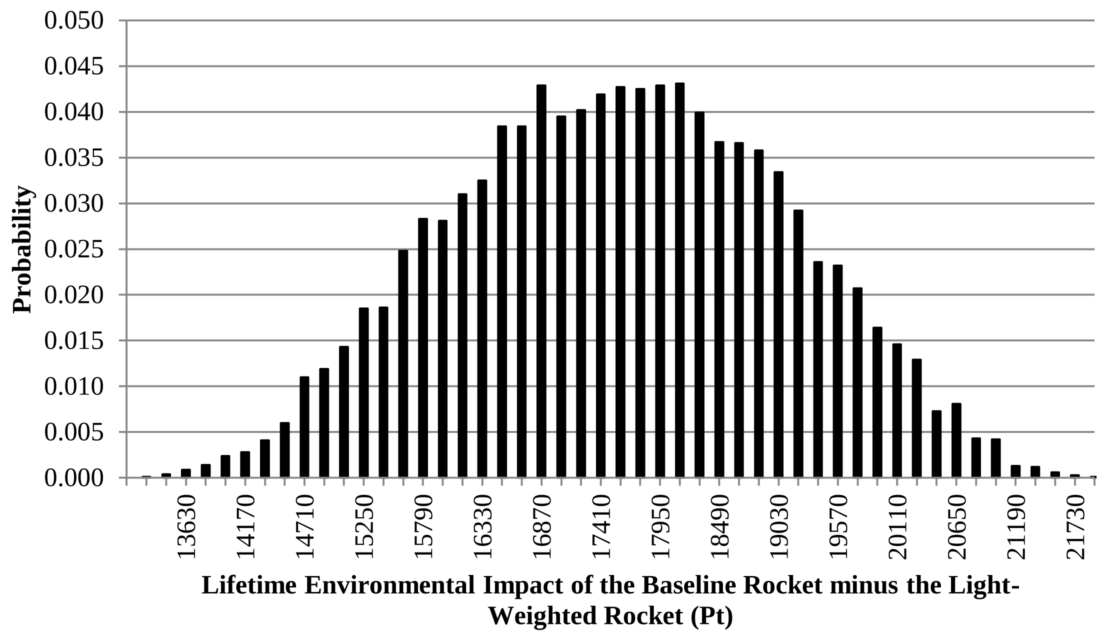


Figure E 25: Probability density function showing the results from the moderate uncertainty analysis on the three stage, 10,000 kg to LEO, N2O4/UDMH Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

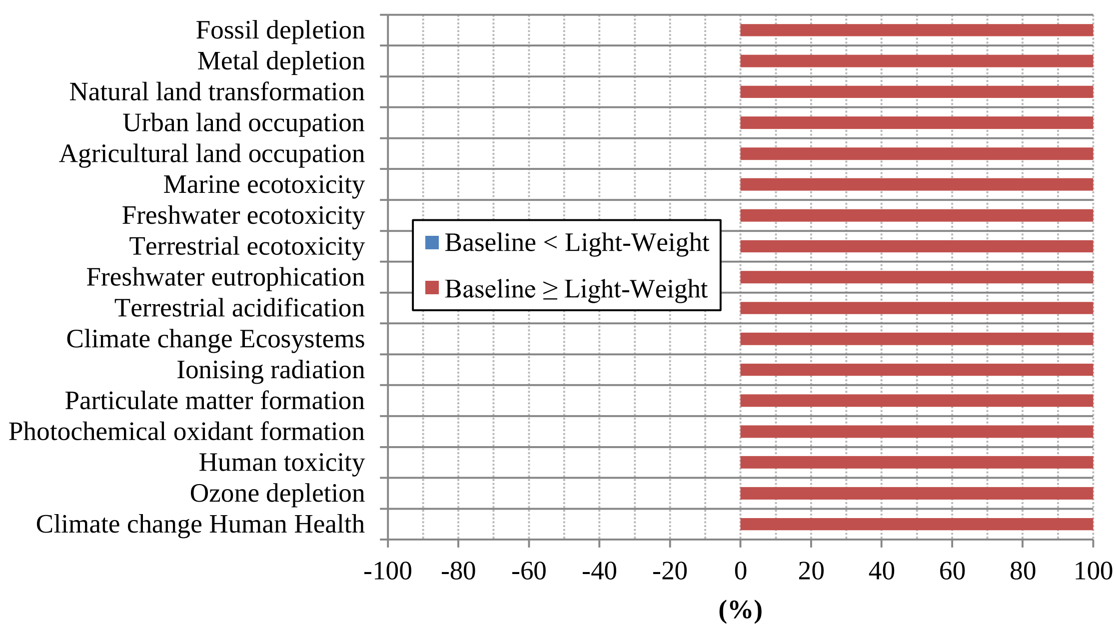


Figure E 26: Categories for which light-weighting was an improvement during the moderate uncertainty analysis, and the likelihood of this occurrence for the three stage, 10,000 kg to LEO, N2O4/UDMH rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

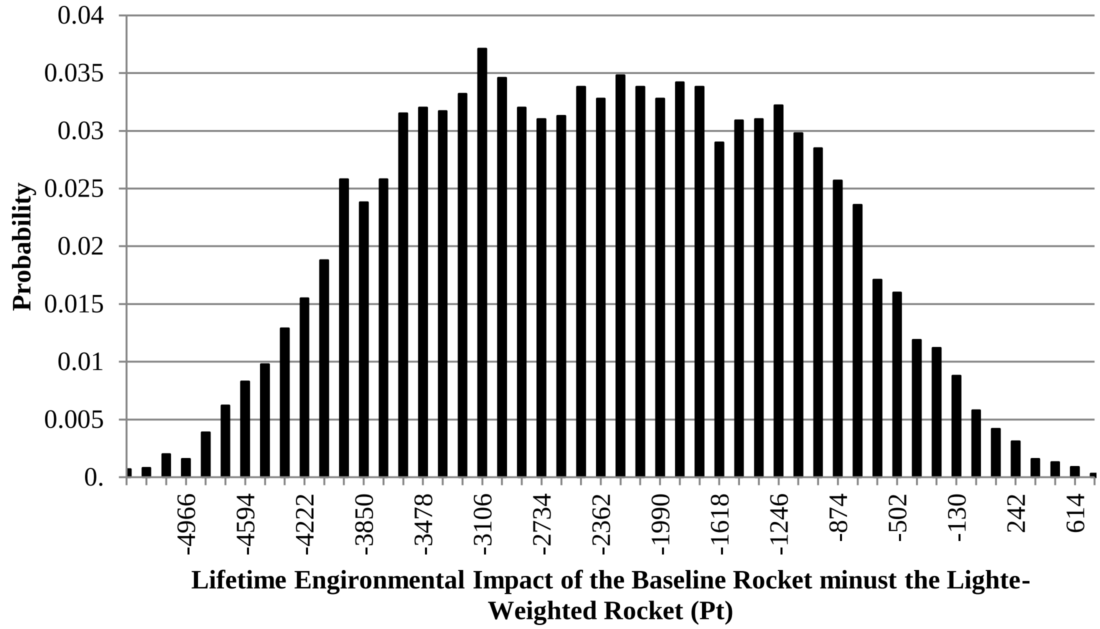


Figure E 27: Probability density function showing the results from the moderate uncertainty analysis on the four stage, 1,500 kg to LEO, Solid Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

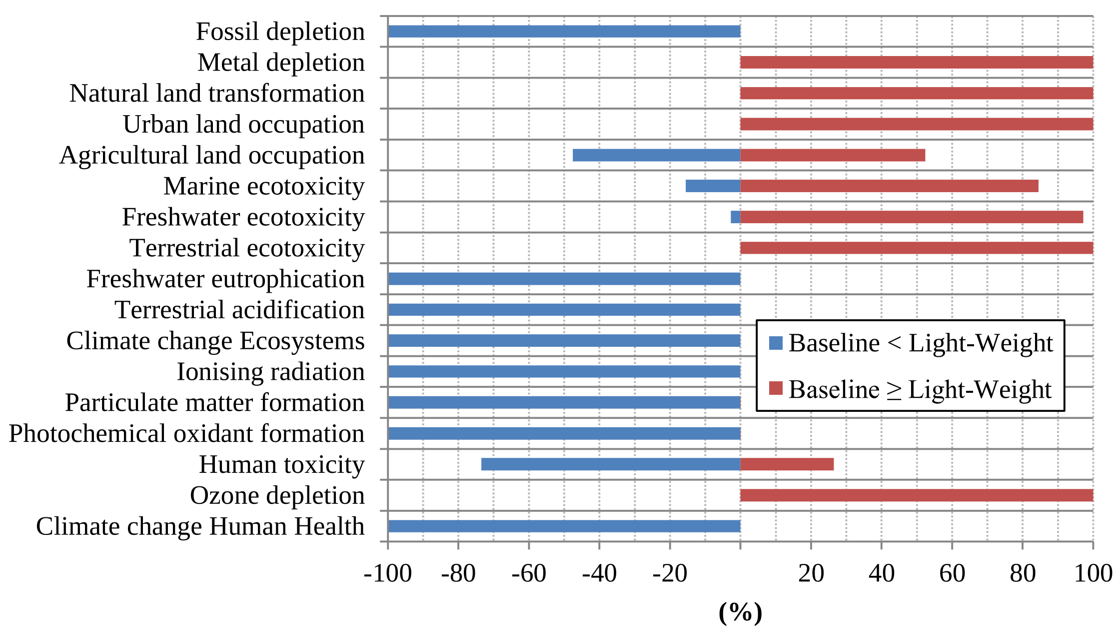


Figure E 28: Categories for which light-weighting was an improvement during the moderate uncertainty analysis, and the likelihood of this occurrence for the four stage, 1,500 kg to LEO, solid rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

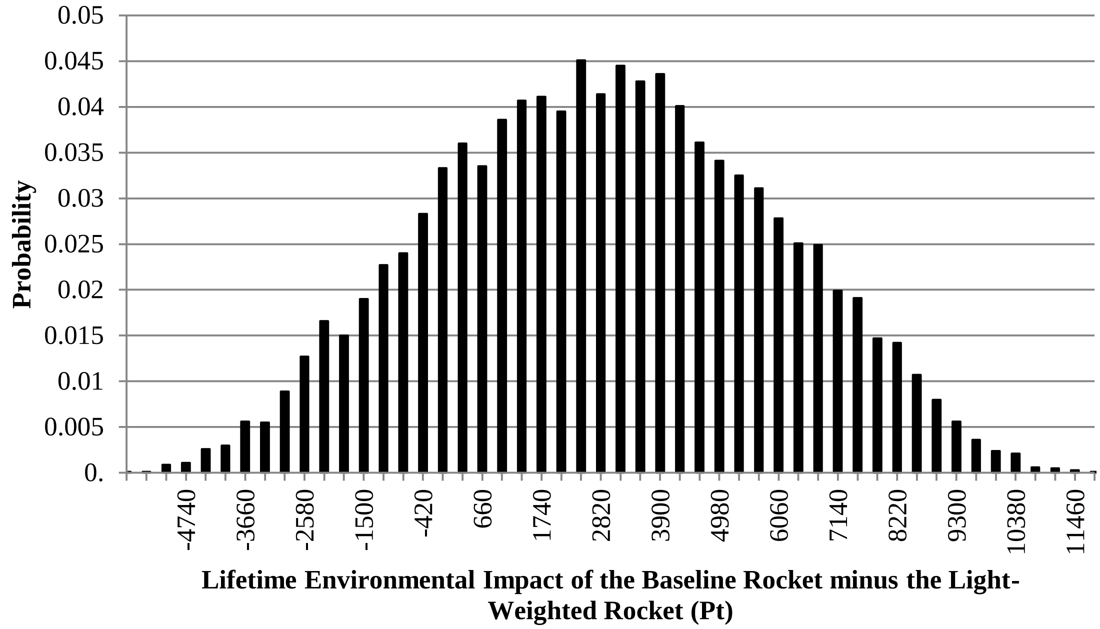


Figure E 29: Probability density function showing the results from the high uncertainty analysis on the two stage, 10,000 kg to LEO, LOX/LH2 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

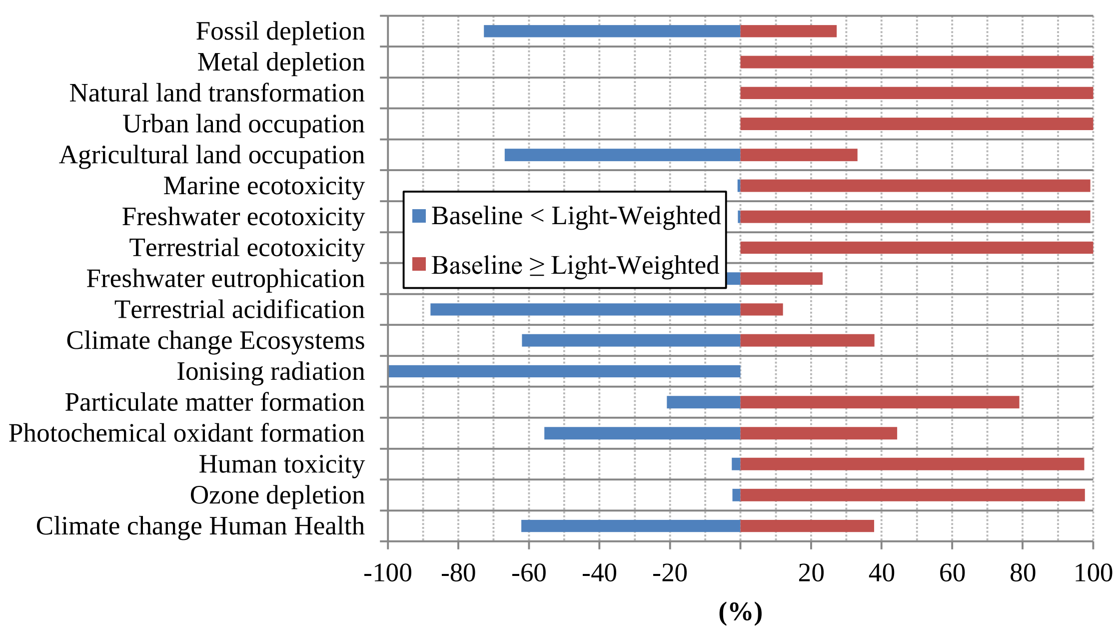


Figure E 30: Categories for which light-weighting was an improvement during the high uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, LOX/LH2 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

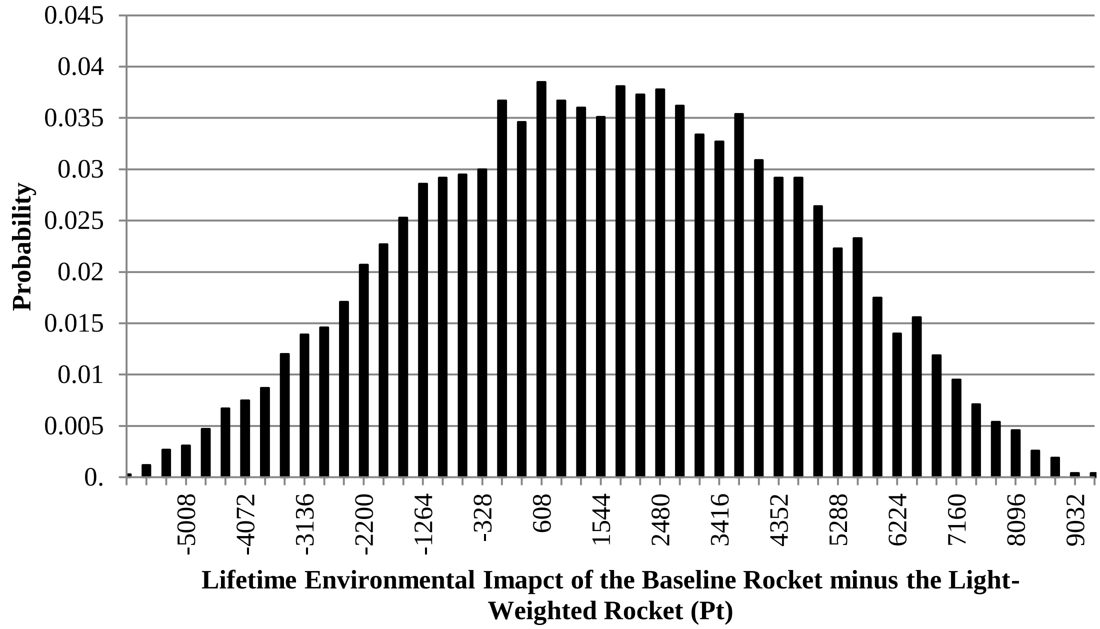


Figure E 31: Probability density function showing the results from the high uncertainty analysis on the three stage, 10,000 kg to LEO, LOX/LH2 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

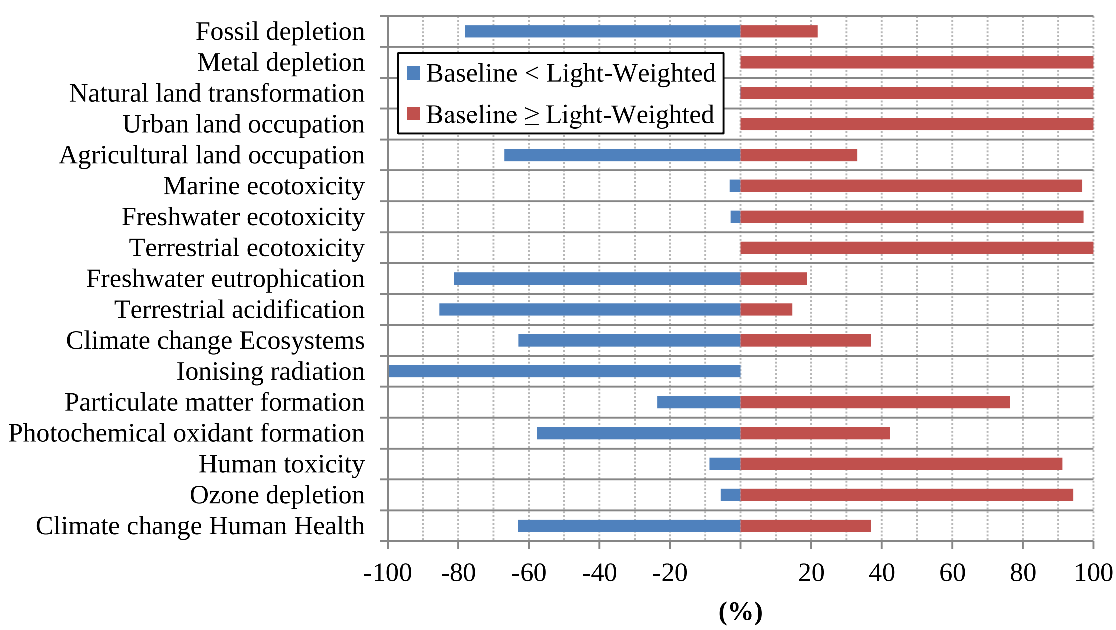


Figure E 32: Categories for which light-weighting was an improvement during the high uncertainty analysis, and the likelihood of this occurrence for the three stage, 10,000 kg to LEO, LOX/LH2 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

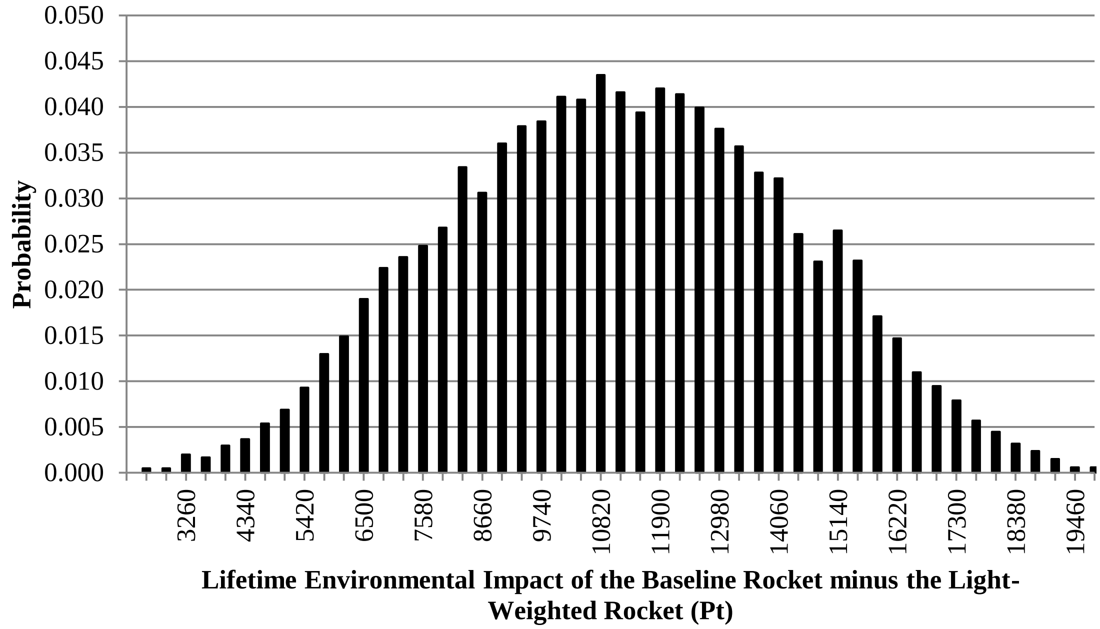


Figure E 33: Probability density function showing the results from the high uncertainty analysis on the two stage, 10,000 kg to LEO, LOX/RP1 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

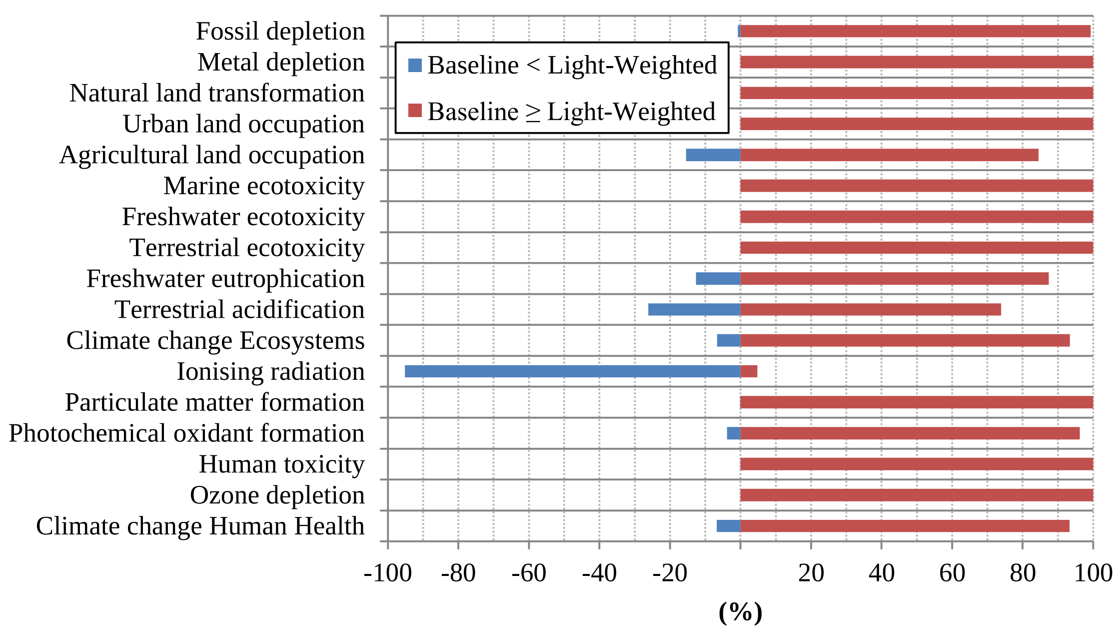


Figure E 34: Categories for which light-weighting was an improvement during the high uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, LOX/RP1 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

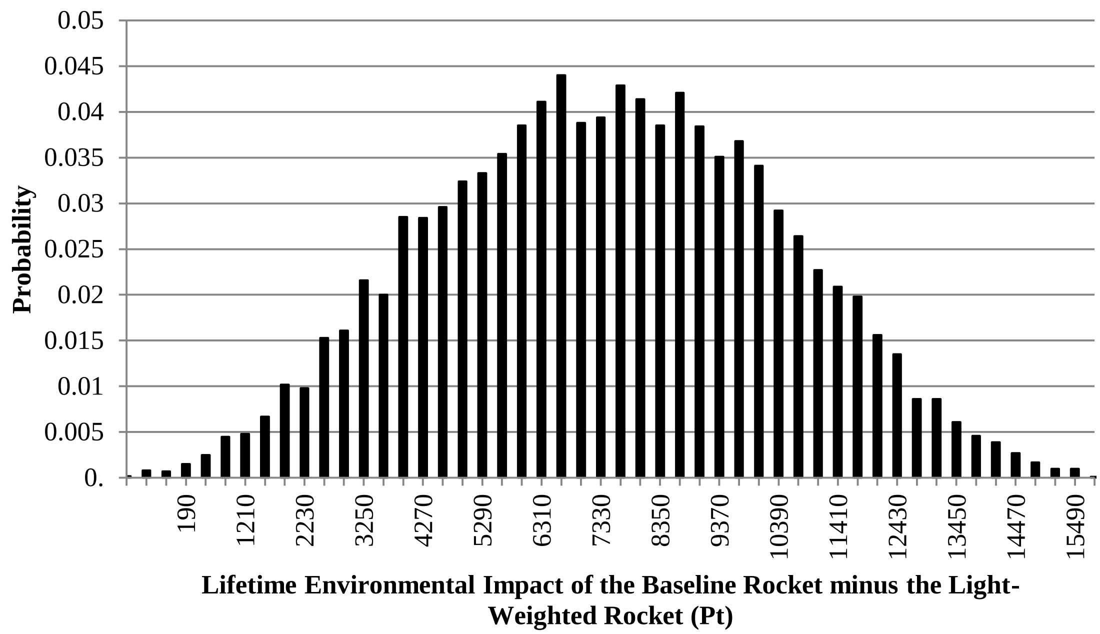


Figure E 35: Probability density function showing the results from the high uncertainty analysis on the three stage, 10,000 kg to LEO, LOX/RP1 Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

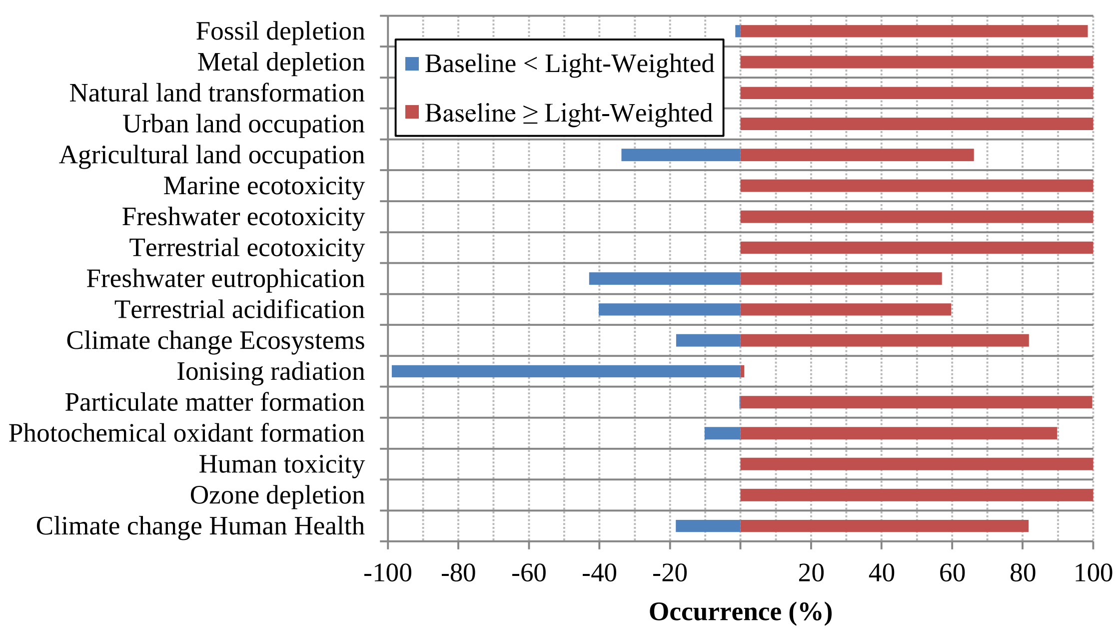


Figure E 36: Categories for which light-weighting was an improvement during the high uncertainty analysis, and the likelihood of this occurrence for the three stage, 10,000 kg to LEO, LOX/RP1 rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

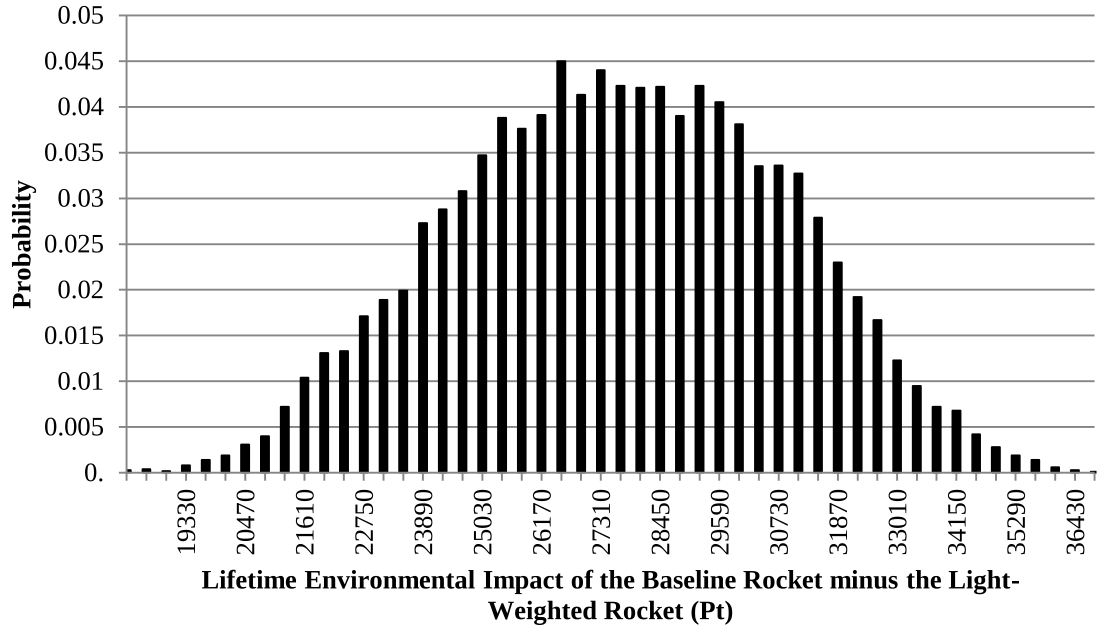


Figure E 37: Probability density function showing the results from the high uncertainty analysis on the two stage, 10,000 kg to LEO, N2O4/UDMH Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

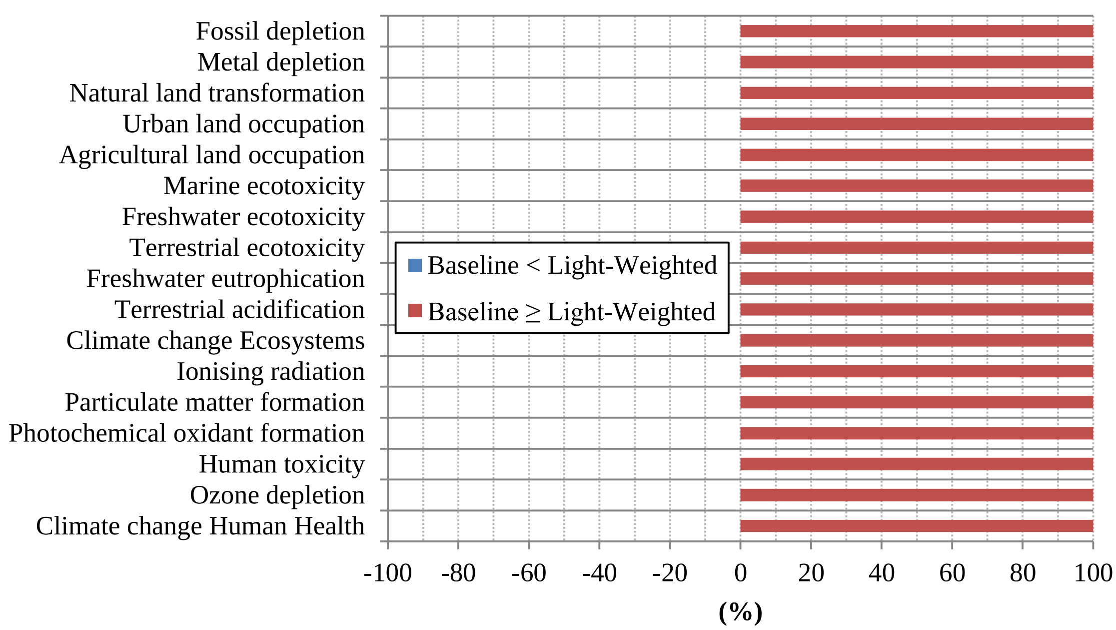


Figure E 38: Categories for which light-weighting was an improvement during the high uncertainty analysis, and the likelihood of this occurrence for the two stage, 10,000 kg to LEO, N2O4/UDMH rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

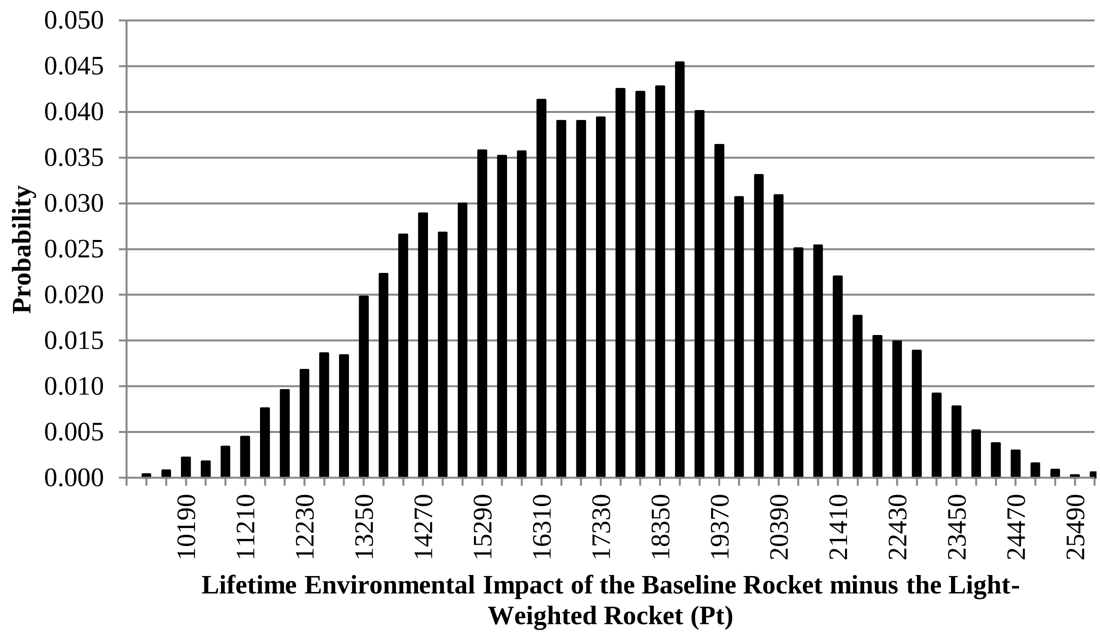


Figure E 39: Probability density function showing the results from the high uncertainty analysis on the three stage, 10,000 kg to LEO, N2O4/UDMH Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

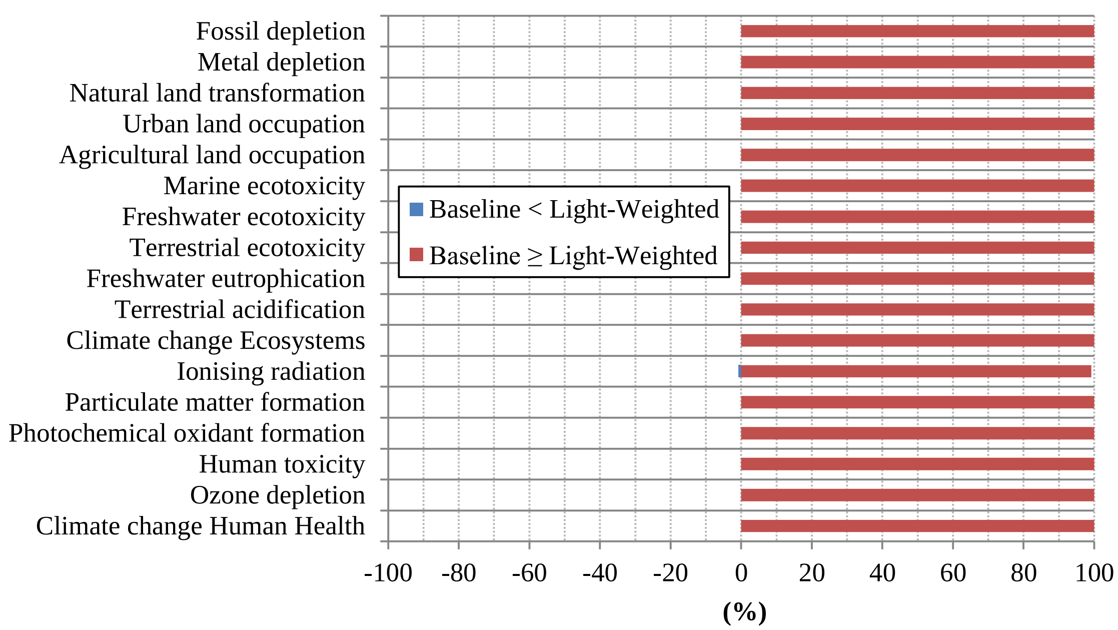


Figure E 40: Categories for which light-weighting was an improvement during the high uncertainty analysis, and the likelihood of this occurrence for the thre stage, 10,000 kg to LEO, N2O4/UDMH rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

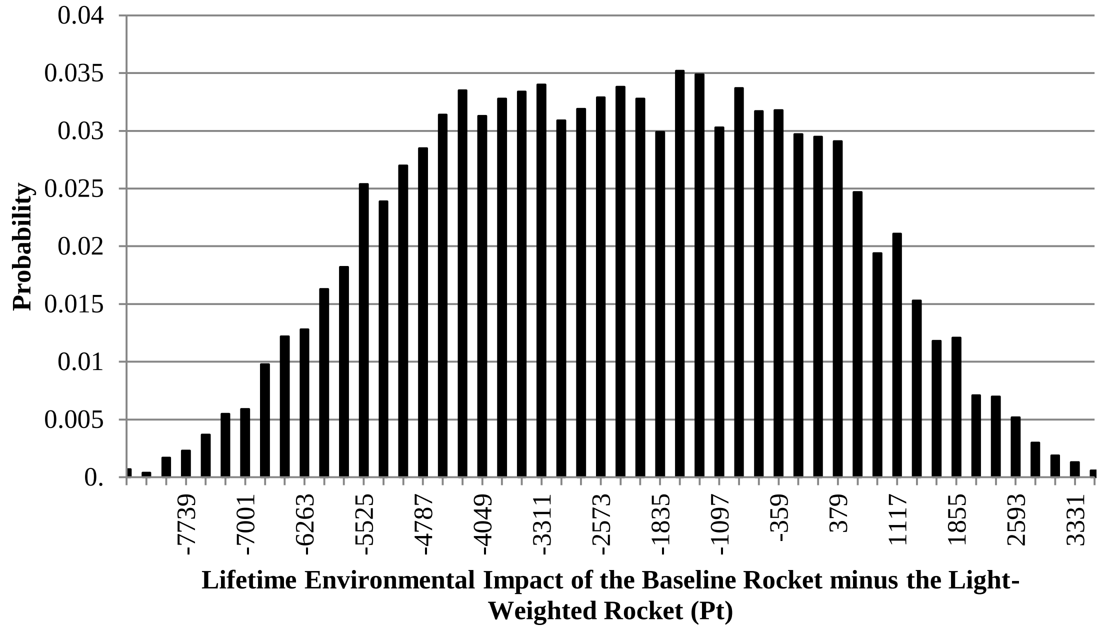


Figure E 41: Probability density function showing the results from the high uncertainty analysis on the four stage, 1,500 kg to LEO, Solid Rocket, depicting lifetime environmental impacts of the baseline rocket minus those of the light-weighted rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

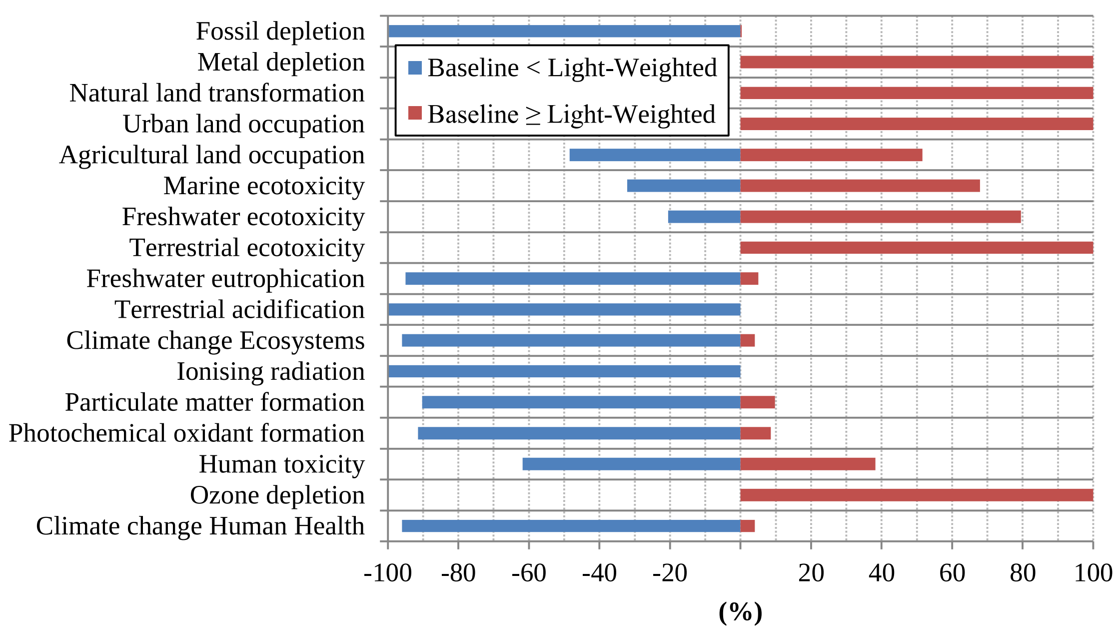


Figure E 42: Categories for which light-weighting was an improvement during the high uncertainty analysis, and the likelihood of this occurrence for the four stage, 1,500 kg to LEO, solid rocket, using the ReCiPe 2008 Egalitarian Endpoint single score indicator

References

Air Force Office of Scientific Research (2009). NASA, Air Force Test Environmentally-Friendly Rocket Propellant. ScienceDaily. online.

Airbus. (2013). "Airbus A330-200." from http://www.airbus.com/aircraftfamilies/passengeraircraft/a330family/a330-200/.

Anderson, Chris (2012). "Elon Musk's Mission to Mars." from www.wired.com

Ariane Space (2006). Soyuz User's Manual. online, Ariane Space.

Ariane Space (2011). Ariane 5 User's Manual. online, Ariane Space.

Ashby, M., H. Shercliff and D. Cebon (2007). Materials. multiple cities, Elsevier, Ltd.

Ashby, M. F. (2005). Material Selection in Mechanical Design. multiple cities, Elsevier, Ltd.

Astrium. (2003). "Welding Technologies Used in Rocket Engine Manufacture." from http://cs.astrium.eads.net/sp/launcher-propulsion/manufacturing/welding-technologies.html.

Bell, B. H. J. (1960). "Platinum Catalysts in Ammonia Oxidation." Platinum Metals Review **4**(4): 122-126.

Box, G. E. P. and N. R. Draper (1987). Empirical Model Building and Response Surfaces. New York, John Wiley & Sons.

Brady, B. B., L. R. Martin and V. I. Lang (1997). "Effects of Launch Vehicle Emissions in the Stratosphere." Journal of Spacecraft and Rockets **34**(6): 774-779.

Bromley, J. (1971). Gas evolution process during the formation of carbon fibres. Carbon Fibres, Their Composites and Applications, London, The Plastics Institute.

Bruhn, E. F., J. I. Orlando and J. F. Meyers (1967). Analysis and Design of Missile Structures. Cincinnati, OH, Tri-State Offset Company.

Busacca, M. (1984). Environmental Considerations of Constructing and Operating a Polygeneration Plant at the John F. Kennedy Space Center. JANNAF Safety & Environmental Protection Subcommittee Meeting. Las Cruces, NM.

Caras, G. J. (1963). Manufacturing Process for Liquid Hydrogen, U.S. Army Missile Command.

Carlsen, L., O. A. Kenesova and S. E. Batyrbekova (2007). "A Preliminary Assessment of the Potential Environmental and Human Helth Impact of Unsymmetrical Dimethylhydrazine as a Result of Space Activities." Chemosphere **67**: 1108-1116.

Carlsen, L., B. N. Kenessov and S. E. Batyrbekova (2008). "A QSAR/QSTR Study on the Environmental Health Impact by the Rocket Fuel 1, 1-Dymethyl Hydrazine and its Transformation Products." Environmental Health Insights **2008**(1): 11-20.

Center, N. L. R. (2013). Composite Cryotank Work Progresses. Space Technology Game Changing Development: Monthly Highlights. online.

Chung, D. D. L. (1994). Carbon Fiber Composites. multiple cities, Butterworth-Heinemann.

Cicerone, R. J., D. H. Stedman, R. S. Stolarski, A. N. Dingle and R. A. Cellarius (1973). Assessment of Possible Environmental Effects of Space Shuttle Operations, University of Michigan.

Damodaran, S. (1991). Evolution of Structure and Mechanical Properties During Carobonization of Polyacrylonitrile-Based Precursor Fibers. Doctor of Philosophy Dissertation, Georgia Institute of Technology.

Das, S. (2011). "Life cycle assessment of carbon fiber-reinforced polymer composites." International Journal of Life Cycle Assessment(16): 268-282.

De Vegt, O. M. and W. G. Haije (1997). Comparative Environmental Life Cycle Assessment of Composite Materials. (online)**:** 37.

Donnet, J.-B. and R. C. Bansal (1990). Carbon Fibers. New York and Basel, Marcel Dekker, Inc.

Duflou, J. R., J. W. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild and K. Kellens (2012). "Towards energy and resource efficient manufacturing: A processes and systems approach." CIRP Annals - Manufacturing Technology **61**(2): 587-609.

Environmental Protection Agency. (2013). "What is sustainability?", from www.epa.gov/sustainability/basicinfo.htm.

EPA. (undated). "Calculations and References." from http://www.epa.gov/cleanenergy/energy-resources/refs.html.

Federal Aviation Administration (2012). 2012 Commercial Space Transportation Forecasts. online, FAA Commercial Space Stransportation and the Commercial Space Transportation Advisory Committee.

Fiedler, A. K., E. Fitzer and F. Rozploch (1973). "PAN Pyrolysis Studied by Gas- and ESR- Analyses." Carbon(11): 426-428.

Fitzer, E. (1989). "PAN-Based Carbon Fibres-Present State and Trend of the Technology from the Viewpoint of Possibilities and Limits to Influence and to Control the Fiber Properties by the Process Parameters." Carbon **27**(5): 621-645.

Fitzer, E. (1990). "Polyaromaten mit Fasertextur - Die modernen Hochleistungs-Carbonfasern." Acta Polymerica **41**(7): 381-389.

Fitzer, E. and W. Frohs (1990). "Modern Carbon Fibres from Polyacrylonitrile (PAN)-Polyheteroaromatics with Preferred Orientation." Chemical Engineering and Technology(13): 41-49.

Fitzer, E., W. Frohs and M. Heine (1986). "Optimization of Stabilization and Carbon Treatment of PAN Fibres and Structural Characterization of the Resulting Carbon Fibres." Carbon **24**(4): 387-395.

Fitzer, E., A. Gkogkidis and G. Jacobsen (1982). Influence of Temperature Increase on Stabilization of PAN. International symposium on carbon: new processing and new applications, extended abstracts. Toyohashi, Japan.

Fitzer, E. and M. Heym (1976). "Carbon fibres-the outlook." Chemistry and Industry(16): 663-676.

Gardiner, G. (2011). Out-of-Autoclave Prepregs: Hype of Revolution? Composites World. online.

Goedkoop, M., A. De Schryver, M. Oele, S. Dusksz and D. de Roest (2010). Introduction to LCA with SimaPro 7, PRe Consultants.

Goedkoop, M., R. Heijungs, M. Huijbregts, A. D. Schryver, J. Struijs and R. van Zelm (2013). ReCiPe 2008 Main Report. online.

Granta (2012). CES EduPack 2012. Granta Design Limited.

Harper International (2009). Carbon Fiber Line Capacity: Historical Perspective. 12th Annual Global Outlook for Carbon Fiber 2009. La Jolla, CA, IntertechPira.

Harper International (2012). Energy Efficiency in the Carbon Fiber Conversion Process. JEC 2012. Paris, France.

Hexcel (undated). Innovations in HexTow Carbon Fiber. online, Hexcel.

Hines, M. E., F. von Hippel and J. Kennish (2002). Biological Effects of Inadvertent Perchlorate Release During Launch Operations, University of Alaska.

Hinkle, C. R. and W. M. Knott III (1985). A Summary of Environmental Effects of Space Shuttle Launches at the John F. Kennedy Space Center, Florida After the First 24 Launches. 152nd Annual Meeting of the American Association for the Advancement of Science. Philadelphia, PA.

Hubbard, J. M. and B. M. Ward (1998). The Multiple Launch Rocket System Final Life Cycle Environmental Assessment Update, Department of the Army.

Humble, R. W., G. N. Henry and W. J. Larson (1995). Space Propulsion Analysis and Design. multiple cities, McGraw-Hill Companies.

Huzel, D. K. and D. H. Huang (1992). Modern Engineering for Design of Liquid Propellant Rocket Engines, AIAA.

International Launch Services (2009). Proton Launch System Mission Planner's Guide. V. E. Nesterov, F. McKenna, Y. O. Bakhbalov and J. Bonner. online, International Launch Services.

ISC Kosmotras (2001). Dnepr User's Guide. online.

Jain, M. K. (1985). Physical and Porphological Changes Druing the Conversion of Acrylonitrile-Based Precursors to Carbon Fibers. Doctor of Philosophy Dissertation, Georgia Institute of Technology.

Jain, M. K. and A. S. Abhiraman (1987). "Conversion of acrylonitrile-based precursor fibres into carbon fibres (Part 1)." Journal of Materials Science(22): 278-300.

Jain, M. K., M. Balasubramanian, P. Desai and A. S. Abhiraman (1987). "Conversion of acrylonitrile-based precursors to carbon fibres (Part 2)." Journal of Materials Science(22): 301-312.

JCMA. (2008). "Automobile and Airplane LCA." from http://www.carbonfiber.gr.jp/english/lcamodel.HTML.

Kalpakjian, S. and S. Schmid (2003). Manufacturing Processes for Engineering Materials. Upper Saddle River, NJ, Prentice Hall.

Kara, S. and S. Manmek (2009). Composites: Calculating their Embodied Energy, The University of New South Wales.

Kara, S., S. Manmek and C. Herrmann (2010). "Global manufacturing and the embodied energy of products." CIRP Annals - Manufacturing Technology **59**(1): 29-32.

Kobe, K. A. and P. D. Hosman (1948). "Catalytic Oxidation of Ammonia to Nitrous Oxide." Industrial and Engineering Chemistry **40**(3): 397-399.

Kuzin, A. I. (1997). Ecological Problems of Space Exploration. Space Technology and Applications International Forum. Albuquerque, NM, AIP Conference Proceedings 387**:** 1341-1346.

Larson, W. J., L. Pranke, J. Connolly and R. Giffen (2007). Human Spaceflight: Mission Analysis and Design, Learning Solutions.

Lenger, Elizabeth Y. (2011). personal communication (email) on 03/01/2011

Lindborg, C. (undated). "Tsyklon." from http://www.fas.org/spp/guide/ukraine/launch/tsyklon.htm.

Lopes, J. V. d. O. F. (2010). Life Cycle Assessment of the Airbus A330-200 Aircraft. Master of Science Thesis, Universidade Tecnica de Lisboa.

Marshall History Office (2000). Milestones in Space Exploration. online, Marshall Space Flight Center.

Morgan, P. (2005). Carbon Fibers and their Composites. Boca Raton, FL, CRC Press.

Moseman, A. (2009). How to Make a (More) Environmentally Friendly Rocket Fuel. Popular Mechanics. online.

Mueller, K. F., R. E. Farncomb, K. L. Wagaman and W. E. McQuistion (1976). New Process for the Production of Unsymmetrical Dimethylhydrazine (UDMH). National Techniocal Information Service, U.S. Department of Commerce. U. S. D. o. t. Navy. United States.

Naqvi, S. M. Z. and A. Latif (1974). Biodegredation of Rocket Propellant Waste, Ammonium Perchlorate, Alcorn State University.

NASA (1970). Solid Rocket Motor Metal Cases. online, National Aeronautics and Space Administration.

NASA (1988). Space Shuttle Orbiter Systems. online, National Aeronautics and Space Administration.

NASA (2004). External Tank Return to Flight Focus Area: Thermal Protection System. online, Marshall Space Flight Center.

NASA/Ames Research Center (2003). NASA Tests Environmentally Friendly Rocket Fuel. ScienceDaily. online.

Norgate, T. E., V. Rajakumar and S. Trang (2004). Titanim and Other Light Metals - Technology Pathways to Sustainable Development. Green Processing Conference. Fermantle, WA.

Orbital Science Corporation (2006). Minotaur I User's Guide. online, Orbital Science Corporation.

Orbital Science Corporation (2006). Minotaur IV User's Guide. online, Orbital Science Corporation.

Orbital Science Corporation (2006). Taurus Launch System Payload User's Guide. online.

Oreskes, N., K. Shrader-Frechette and K. Belitz (1994). "Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences." Science **263**(5147): 641-646.

PAC-3 Environmental Assessment Team (1997). PATRIOT Advanced Capability-3 (PAC-3) Life-Cycle Environmental Assessment, U.S. Army Space and Strategic Defense Command.

Peebles, L. H. (1995). Carbon Fibers: Fromation, Structure, and Properties. multiple cities, CRC Press.

Popp, R. J., B. A. Ridley, J. A. Neuman, L. M. Avallone, D. W. Toohey, P. F. Zittel, O. Schmid, R. L. Herman, R. S. Gao, M. J. Northway, J. C. Holecek, D. W. Fahey, T. L. Thompson, K. K. Kelly, J. G. Walega, F. E. Grahek, J. C. Wilson, M. N. Ross and M. Y. Danilin (2002). "The Emission and Chemistry of Reactive Nitrogen Species in the Plume of an Athena II Solid-Fuel Rocket Motor." Geophysical Research Letters **29**(18).

Powell, R. (1968). Hydrazine Manufacturing Process. Park Ridge, NJ, Noyes Development Corporation.

Pratt & Whitney (1966). Design Report for RL10A-3-3 Rocket Engine, Pratt & Whitney Aircraft.

PRE Consultants (2000). Eco-indicator 99 Manual for Designers. online, Ministry of Housing.

PRe Consultants. ((undated)). "About SimaPRO." from http://www.pre-sustainability.com/simapro-lca-software.

Proctor, P. C. (2002). Boeing Ascendant. Boeing Frontiers. online. **1**.

Rankine, R. K., J. P. Chick and G. P. Harrison (2006). "Energy and carbon audit of a rooftop wind turbine." Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy(220): 643-654.

Reap, J., F. Roman, S. Duncan and B. Bras (2008). "A survey of unresolved problems in LCA Part 2: impact assessment and interpretation." International Journal of Life Cycle Assessment **13**: 374-388.

Reap, J., F. Roman, S. Duncan and B. Bras (2008). "A survey of unresolved problems in life cycle assessment Part 1: goal and scope and inventory analysis." International Journal of Life Cycle Assessment **13**: 290-300.

Riddle, R. A. and R. A. Beckwith (1984). Development of Test and Analysis Methods for Thick-Wall, Graphite/Epoxy Filament-Wound Composite Materials Fracture Toughness. Seventh Conference on Composite Materials: Testing and Design. J. M. Whitney. Philadelphia, PA, American Society for Testing and Materials.

Rocketdyne (1998). Space Shuttle Main Engine Orientation. online.

Roscoe, H. K. and A. K. Hind (1993). "The Equilibrium Constant of NO2 with N2O4 and the Temperature Dependence of the Vixible Spectrum of NO2: A Critical Review and the Implications for Measurements of NO2 in the Polar Stratosphere." Journal of Atmospheric Chemistry **16**: 257-276.

Ross, M., D. Toohey, M. Peinemann and P. Ross (2009). "Limits on the Space Launch Market Related to Stratospheric Ozone Depletion." Astropolitics **7**(1): 50-82.

Ross, M. N., M. Y. Danilin, D. K. Weisenstein and M. K. W. Ko (2004). "Ozone Depletion Caused by NO and H2O Emissions from Hydrazine-Fueled Rockets." Journal of Geophysical Research **109**.

Ross, M. N., D. W. Toohey, W. T. Rawlins, E. C. Richard, K. K. Kelly, A. F. Tuck, M. H. Proffitt, D. E. Hagen, A. R. Hopkins, P. D. Whitefield, J. R. Benbrook and W. R. Sheldon (2000). "Observation of Stratospheric Ozone Depletion Associated with Delta II Rocket Emissions." Geophysical Research Letters **27**(15): 2209-2212.

Russell, C. K. and R. Carter (2007). "Friction Stir Welding of GRCop-84 for Combustion Chamber Liners." Journal of Propulsion and Power **23**(4): 756-762.

Rydh, C. J. and M. Sun (2005). "Life cycle inventory data for materials grouped according to environmental and material properties." Journal of Cleaner Production(13): 1258-1268.

Scaled Composites. (undated). "Oxidizer Tank and CTN." from http://www.scaled.com/images/uploads/pdf/Posterboard_-_Oxidizer_Tank_and_CTN.pdf.

Schmidt, E. W. (1984). Hydrazine and its Derivatives. multiple cities, John Wiley & Sons.

Seitzen Jr., F. (2005). "The Greening of Rocket Propulsion." Aerospace America **43**(7): 28-35.

Simonsen, M. (2009). Kerosene - Jet Fuel. online, Vestlandsforsking**:** 15.

Sittig, M. (1980). Carbon and Graphite Fibers: Manufacturing and Applications. Park Ridge, NJ, Noyes Data Corporation.

Space1. "Apollo Service Module & LM RCS Thruster." from http://www.space1.com/Artifacts/Apollo_Artifacts/SM_RCS_Thruster/sm_rcs_thruster.html.

SpaceX (2009). Falcon 9 Launch Vehicle Payload User's Guide. online, SpaceX.

SpaceX. (2012). "Falcon 9 Flight 1 in Pictures." from http://www.spacex.com/F9-001.php#.

SpaceX. (2013). "Our Reusability Designs." from http://spacex.com/multimedia/videos.php?id=0.

Speight, J. G. (2006). The Chemistry and Technology of Petroleum, Fourth Edition, CRC Press.

State Space Agency of Ukraine (2013). Zenit-3SL Launch Vehicle. online.

Steinberger, R. and P. D. Dreschel (1969). Manufacture of Cast Double-Base Propellant. Propellants Manufacturing, Hazards, and Testing, Washington D.C., American Chemical Society.

Strong, B. (2008). Fundamentals of Composites Manufacturing. Dearborn, MI, Society of Manufacuting Engineers.

Stry, B. (2012). Innovations in Oxidation Technology to Enable Market Growth. Composites World 2012, La Jolla, CA.

Sturm, A. (undated). Glossary of Environmental Terms. online, Ellipson Ltd.

Sutton, G. P. and O. Biblarz (2001). Rocket Propulsion Elements. multiple cities, John Wiley and Sons, Inc.

Suzuki, T., T. Odai, R. Hukui and J. Takahashi (undated). LCA of Passenger Vehicles Lightened by Recyclable Carbon Fiber Reinforced Plastics. online, The University of Tokyo.

Suzuki, T. and J. Takahashi (2005). Prediction of Energy Intensity of Carbon Fiber Reinforced Plastics for Mass-Produced Passenger Cars. The Ninth Japan International SAMPE Symposium.

Suzuki, T. and J. Takahashi (undated). LCA of Lightweight Vehicles by Using CFRP for Mass-Produced Vehicles, The University of Tokyo.

Taeber, R. J. and D. P. Weary (1973). Apollo Experience Report - Command and Service Module Reaction Control Systems, NASA.

The Boeing Company (2006). Delta II Payload Planners Guide. online, The Boeing Company.

The Japan Carbon Fiber Manufacturers' Association (2008). Automobile and Airplane LCA: "JCMA Model". online.

Toray Carbon Fibers. (2008). "Intermediate Modulus Carbon Fibers." from http://www.toraycfa.com/intermediatemodulus.html.

Trends in Japan (undated). Hera-Shibori: Metal Spinning. Trends in Japan. online.

United Launch Alliance (2007). Delta IV Payload Planners Guide. online.

United Launch Alliance (2010). Altas V Launch Services User's Guide. online, United Launch Alliance.

United Start (2006). Start-1 Space Launch System: User's Handbook. **1**.

United States General Accounting Office (1992). Rocket Tests in Mississippi to be Heavily Restricted.

Van Acker, K., I. Verpoest, J. De Moor, J.-R. Duflou and W. Dewulf (2009). "Lightweight materials for the automotive: Environmental impact analysis of the use of composites." Revue de Metallurgie **106**(12): 541-546.

Wilhite, A. W. (2012). AE 6322 Lecture Notes. online, Georgia Institute of Technology.

Wright, D. (2012). Debris from North Korea's Launcher: What It Shows. All Things Nuclear. online, Union of Concerned Scientists.

Yaodong, L. (2010). Stabilization and Carbonization Studies of Polyacrylonitrile/Carbon Nanotube Composite Fibers. Doctor of Philosophy Dissertation, Georgia Institute of Technology.

Zhang, X., M. Yamauchi and J. Takahashi (2011). Life Cycle Assessment of CFRP in Application of Automobile. 18th International Conference on Composite Material. Jeju Island, Korea.

Zushi, H., J. Takahashi, K. Kageyama, H. Murayama, H. Nagai and J.-i. Matsui (2003). "Life Cycle Assessment and Long Term CO2 Reduction Estimation of Ultra Lightweight Vehicles Using CFRP." Key Engineering Materials **243-244**: 45-50.