Propellant Pollution

What is the price for Access to Space?

September 2022

What are propellants?

The contemporary route to orbiting any payload requires chemical propulsion – involving a range of chemicals that either undergo energy-heavy manufacturing processes or demand highly specialised storage and handling.

The Cradle to Grave story

To ignore these wider aspects creates a false understanding of the environmental impact. For instance, the manufacturing processes used to produce propellants as well as to store and use them significantly increases the total volume of identifiable and measurable by-products.

A Proxy Mission to Low Earth Orbit

The best approach for comparing contemporary propellant combinations is to evaluate a standard, proxy mission. Here, the objective of placing a 300kg payload into sun-synchronous orbit was used to compare the like-for-like environmental impact of modern propellant mixes.

What is the Price for Access to Space?

Up to now, the number of launches per year has probably had a negligible impact on global warming, but we are seeing an almost exponential increase in launch cadence, can this growth be tolerated - and how must we respond?

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Introduction

The current interest for developing viable green propellants has existed for some time in the history of modern propulsion, driven by a need to develop cleaner 'greener' alternatives to conventional propellants because of their highly toxic nature, (e.g. Hydrazine and its family of derivatives[1]). The onset of this attention to safer alternatives was inspired by the Space Race in the 1950s and '60s, where concern over environmental effects generated concerns within the industry.[2]

From these origins, the underlying requirement for an environmentally friendly propellant focused on addressing combustion emissions and their impact on the atmospheric, terrestrial environment and biological species.

Today, we have entered a new space race, dominated by the speed and cost of accessing orbital domains through wide-scale commercialisation. This means – and is already being clearly demonstrated by – a large number of new, smaller format launch vehicles and satellites (aka small launchers and smallSats) entering the market. As these new designs are developed, the space manufacturing supply-chain and launch service providers are undergoing rapid commercial adaptation where these smaller formats are enabling the cost of access to come down considerably, even as the size of space constellation networks gathers pace.

Combined, this is leading to innovations in propulsion, such as new, "cleaner" concepts in spacecraft design. For launch vehicles, however, fundamental needs must continue to be met, which is restricting our ability to develop propellants that are cleaner - to make and use - whilst also providing the power (thrust) required to propel even the new small launcher formats currently under development.

Many chemicals have been proposed as promosing, yet unrealised, replacements to the conventional suite of fuels and oxidisers in use; yet whilst they show theoretical promise, much more research is required to fully evaluate their practical use.

Based on the data in the table above, the reader is advised to appreciate that the majority of the new propellants under development are **only viable for low-mass spacecraft and their in-orbit management**. Where other research is focused on propellants for larger formats, including launch vehicles, the successful use of these is some time away, although we may see some cross-fertilisation of technologies and chemistry between these two schools of investigation.

The key to any new propellant under development is including an understanding of the broader environmental impact they will have. It is simply not sufficient to consider the propellant's combustion whilst ignoring the full cradle-to-grave life cycle, a cycle which includes the processing and manufacturing of raw materials and compounds along with storage and handling requirements.

It should also be noted that creating a new green propellant in the absence of the safety risks to those handling it in the course of their work would be foolhardy and unhelpful. And it goes without mention that any new such propellant has to be competitively priced against the incumbents to make it attractive to the market. [3, 4]

In all honesty, the green propellant sector is in its' infancy with the majority of space agencies and industry players yet to adopt green propellants at any notable level. Currently, they account for up to 38% of the total mass of all propellants consumed for launch globally, if LOx LH_2 is considered a green combination. Certainly, LOx Kerosene (RP1) is the most popular combination.

Whilst industry market research estimates the number of launches is likely to double by 2030, the types of vehicle and propellant combinations used can only be guessed at. Thus, the cumulative impact on the environment is very difficult to assess. [5].

The industry has a choice to make – stand by its values of high-quality engineering supported by a foundation of evidence-based science to ensure it can take responsibility for its' future environmental impact. Or, tacitly compare it like-for-like with other industries to imply that there really isn't anything to worry about.

This white paper is the culmination of a six-month research project by Nojus Zidonis, an undergraduate engineer at Manchester University, who was funded as a UKSA SPINtern with Plastron UK Ltd during 2021.

Plastron UK is a start-up in the UK space industry focused on safety in the upstream setting, drawing on over 40 years of propulsion and propellant handling expertise. We see this report as the start of a significant move that will contribute to truthful and evidence-based environmental-aligned improvements in the NewSpace sector as it develops over the coming decade.

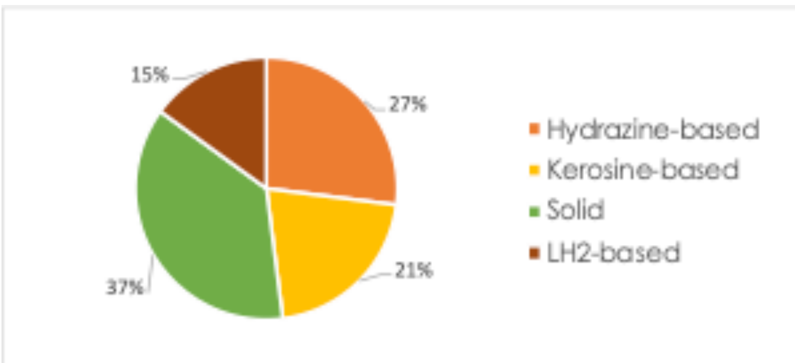


Figure 1: Propellant combination distribution over launches in 2020

Overview

This report is intended to help any reader understand fundamentally what is happening in propulsion science and engineering in order to inform a fair and open debate. To this extent, this report will sequentially explain necessary aspects of propulsion science without causing confusion, incrementally building a definition of the propulsion 'ecosystem' so that the 'cradle-to-grave' concept is understood.

It goes on to introduce the main propellants in use today, with an overview of their manufacture. This leads to an explanation of the chemical combustion (decomposition) process and the by-products released with an explanation of the environmental and biological risks they are associated with.

Finally, we provide to the best of available knowledge a like-for-like comparison between popular and ascendant propellant combinations, ultimately using a proxy mission of placing a standard payload mass into a standard orbit.

Sometimes comparisons to more commonplace situations help us appreciate the contextual issues more clearly. So perhaps let's start off with the following:

On average, a petrol-driven car exhaust will release around 3,000Kg of carbon-based derivatives over the course of a year. This is about the same amount generated when placing 1Kg of payload into a Low-Earth Orbit (circa, 500Km altitude).

▶ The price for Access to Space

Talk of 'green propellants' has been on the rise in recent years, creating an environment of misinformation over the true impact these chemicals have on the environment. The arguments are often very selective in assessing the environmental impact and frequently ignore full comprehension of the chemical processes involved during combustion, with most omitting the environmental price of manufacture. This is to the detriment of the industry as it contributes to a 'laissez-faire' attitude, which suggests the environmental impact of propellants can be seen to be negligible.

This white paper, researched and written during 2021-22 with funding from the UK Space Agency, aims to reset the debate. This is timely, it should be noted, as this paper was researched in parallel to NASA, ESA and leading universities globally publishing key papers describing environmental concerns and risks resulting from propellant use. Here, we asks the reader to consider some essential framing; this will help you to qualitatively better understand the impact of propellant usage in launch. Before reading any further, please read the following:

3.

There is no such thing as a green propellant **for use in launch vehicles**; even liquid oxygen/liquid hydrogen combinations have an environmental price-to-pay in manufacture.

2.

The cradle-to-grave impact of propellants has to consider raw materials processing, handling, storage and transportation as well as transfer (into launch vehicles), combustion and distribution of exhaust products.

1.

There are physical laws that determine the greatest extent to which propellants combust and generate energy.

What are propellants?

And how do they work? The contemporary route to orbiting any payload requires chemical propulsion – involving a range of chemicals that usually undergo energy-heavy manufacturing processes and demand highly specialised storage and handling.

Thrust: The basic concept is that by combining a fuel with an oxidiser, the reactive force resulting from their combustion provides the force needed to push the launch vehicle up through the atmospheric regions. By considering the internal combustion engine (ICE) used in road vehicles, the reader can draw loose – but viable – comparisons: an ICE running on petrol requires the oxygen present in air to produce the explosive combination for running the engine. The resulting exhaust gas is entirely toxic in its blend of gases (CO_2, SO_2, VOCs) and solids (micro particulates including soot).

The chemical combinations used in rocket propulsion also generate gaseous by-products, which in the concentrations generated, can be judged to deserve analysis – how dangerous are they to living organisms in the immediacy? How do these gases interact with the atmosphere and what is the impact of this? How quickly can natural processes absorb and contain these by-products so that critical pollution or other thresholds are not reached?

Let's take a look at propellants – the oxidisers (oxygen providers) and the fuels and see what combinations exist – both those that have been in use and will continue to do so, as well as some others which are generating interest in the space sector.

Let's also tackle one fundamental question which relates to that suspicious, '*So what?*' some readers may already be thinking – is this really a problem or are we doing this for the sake of some marketing headlines?

Historically, propellant configurations have accounted for a modest impact on the environment during the "LegacySpace" period (ie, the top-down government-led industry base which has been leading the industry since the 1950s). However, we are now in the seond decade of NewSpace, where growth is fueled by minaturisation, more products reaching market sooner and much more investment supporting start-ups in the upstream setting. For example, consider the following:

There are currently over 160 new launch vehicle concepts under development globally. Even with the expected attrition rate driven by failures of launchers (estimated at 93%) as well as by a limited quantity of spacecraft requiring orbital access in the short-term, we can expect to see a 100% increase in the number of launches within the next decade.

The fundamental driver for launch is, of course, payloads demanding orbital access. Whilst the growth in the smallSat market is only just beginning to uptick, this is expected to grow significantly as governments and commercial entities identify and invest into sovereign orbital capabilities intended to underpin security, communications and economic growth.

The ease of use and applicability to small launchers of solid propellants is and will lead to many vehicles under development to use them or a combination of solid and liquid/ solid and gas (hybrid engines). These pollute far more effectively than traditional liquid combinations and tend to produce far more in the way of black carbon particulate, which is particularly damaging, especially in those regions of the atmosphere where they collect.

The growth in launch vehicles will also increase demand for propellants, which in turn will increase pollution risks from terrestrial manufacture and storage locations throughout the atmospheric regions.

The growth in controllable spacecraft will increase manufacturing demand for propellants used in spacecraft orbit control. The spectrum of propellants used for orbit control are not covered in this report, it must be noted, but given the use of anything from semi-rare gases and inert water to green-but-toxic chemicals (such as hydroxyl ammonium nitrate-based propellants, hydrogen peroxide) and highly toxic hydrazine fuels, at the very least a nod that there is an impact to consider is justified.

The propellants

The vast number of potential combinations meant that it was impossible to look at all the available fuel and oxidizers within the scope of this paper. Rather than select random combinations, similar (and more frequently used) combinations to those selected for the ESA Clean Space Initiative propellant life cycle study conducted by Schabedoth et al. [8] were selected. Those considered are listed and discussed below.

Liquid Oxygen (LOX)

Liquid oxygen has emerged as by far the most popular oxidizer on the market. It has seen extended use throughout history ever since its appearance in the first liquid-fuelled rocket. It was used to propel World War II V2 missiles; during the Cold War it saw use on both US Redstone and Atlas projects, and later became the oxidizer of choice in the ascent stages of the Apollo Saturn rocket. The Space Shuttle Main Engine also used liquid oxygen. Its' reputation is as prominent today: in 2020, liquid oxygen has been utilised in more than 70% of rockets launched.

High Test Peroxide (HTP)

High-test Peroxide, a highly concentrated solution of hydrogen peroxide, is a storable oxidizer. It was developed in early 20th century Germany, where it soon became a substitute for liquid oxygen in military applications, owing to its' non-cryogenic storability potential. During the early stages, it saw use in the infamous rocket-powered aircraft interceptor, the Messerschmitt Me 163 Komet (where the HTP had the propensity to leak into the cockpit after a hard landing, dissolving the hapless pilot in the process). It was also used in German missile development programmes. In the mid-20th century, it was extensively studied by a variety of organisations interested in using it as an oxidizer; however, its relatively high freezing point, with the inconvenience of its' solution, meant that it was largely discarded in favour of other options. Largely forgotten, it became known as "the propellant that never made it", at least in the West, although the UK pursued an obsessive interest in HTP with their discarded launcher program Black Arrow and with the air-deployed Blue Steel nuclear missile. Russia, however, has used hydrogen peroxide for decades. More serious interest in hydrogen peroxide has seen a revival in the late 20th century, with Skyrora using it as the preferred oxidiser in their launch vehicle. It is also being used in satellite propulsion by companies such as Benchmark.

Dinitrogen Tetroxide

Dinitrogen tetroxide, also known as nitrogen tetroxide or simply as its chemical formula N_2O_4, is a common, storable oxidizer. Widely used in the farming industry as a precursor to fertiliser, it came to be of interest to NASA due to its hypergolic reaction with hydrazine. Its' first major application in rocketry was in the Titan programme. From then on, it has been commonly used with a variety of hydrazine derivatives. These days, it is most commonly paired with UDMH in launchers and contributes to around a tenth of rocket launches yearly. It is further used in satellite propulsion and long-term space missions, where storability requirements limit other options, in the form of MON or Mixed Oxides of Nitrogen, a combination of N_2O_4 and nitric oxide (NO).

Rocket Propellant-1 (RP-1)

Rocket Propellant-1, also known as Refined Petroleum-1 or refined Kerosene, is the trademark rocket fuel. Formulated specifically as a replacement for varying-quality petrol and Kerosene used in early space propulsion, RP-1 has been used extensively for a variety of missions. A "jack of all trades" option, RP-1's most prominent uses are in NASA's Titan and Saturn launchers, the Soviet Energia super-heavy launcher and many modern launchers, such as the SpaceX Falcon series. These days RP-1 is almost exclusively paired with liquid oxygen; and in this configuration is a propellant of choice in nearly half of launches today. In terms of future launch vehicles, a number are considering an RP-1 (or equivalent)/ HTP combination.

Hydrazine

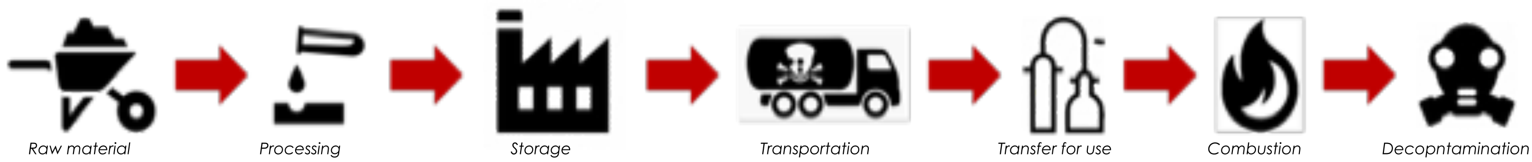
First concentrated by Dr Walter in the early 20th century, hydrazine quickly became a staple propellant option. It was first put to use in anger in the Messerschmitt 163-B interceptor as both a gas generator by reacting with potassium permanganate, and as a bipropellant mixture with hydrogen peroxide. It was noted as a good monopropellant option (a role it still plays in satellite propulsion) due to its' ability to rapidly catalytically decompose, and then the discovery of its hypergolicity with many fuels solidified its' presence in the market. Owing to its high storability, hydrazine and its' derivatives were used in a variety of military and space applications. There is a move to phase out hydrazine due to its toxicity and carcinogenic characteristics, with the (flawed) argument that it is quicker and easier to load supposed "green" propellants. Certainly, the use of hydrazine in Western launchers seems to have withered. Despite that, some of its derivatives (such as UMDH) are still of importance. In launcher applications, it finds use in a tenth of launches. Its' use in military applications and satellite propulsion is as prominent as ever.

Ammonium Perchlorate Composite Propellant

Ammonium perchlorate composite propellant, or APCP for short, is a modern solid propellant option where fuel and oxidizer parts are bound together in a homogeneous mixture. Using ammonium perchlorate as its primary oxidizer, aluminium as fuel and HTPB as a binder it is commonly used in booster application. A highly promising solid propellant, its recent uses include roles as the propellant in Space Shuttle, SLS and Ariane 5 solid boosters, and NASA's Mars Exploration Rover descent package.

The Propellant Life Ecosystem

To ignore the wider environmental effects creates a false understanding of the overall impact. For example, the cryogenic combination of liquid hydrogen and liquid oxygen can easily be described as 'green' since the combustion results in water vapour. However, the manufacturing processes used to produce these chemicals as well as to store them and use them significantly increases the carbon-based derivatives (although it is recognised the production of soot particulate is only prevalent in hydrocarbon-based fuel combustion). In addition, water vapour is not a desirable atmospheric by-product.



THE PROPELLANTS RESEARCHED - AND WHY

The present-day rocket launcher propellant market consists of many different propellants. Despite that, the majority of propellant configurations account for little impact. Some propellants, such as hydrazine, despite being widely used in the past, are being phased out due to their toxicity. Others, like the aforementioned new 'green' propellants, are primarily used in satellite propulsion, while largely avoiding the launcher market itself. As such, they do not account for a significant proportion of total propellant consumption – in 2020 being utilised only in 15% of the launches. As such, they do not play a significant part in present-day issues; and were disregarded in favour of conventional propellants, whose overall exerted impact is significantly higher. These days, four primary propellant configurations are employed in virtually all large-scale operations (See figure 1). They served as the basis for the propellant selection in this paper. Furthermore, HTP – High Test Peroxide – was also included, owing to its resurgence in the private sector in recent years. For the solid propellant choice, APCP was chosen for its positive future outlook and widespread use.

Each of these propellants have been described above, with the actual propellant combinations as follows:

LOX / LH2	LOX / RP1	N_2O_4/UDMH	HTP / RP1	APCP
Cryogenic	**Refined**	**Hypergolic**	**Refined storable**	**Solid**

Mapping Our Research onto the Ecosystem

Within this section, a selection of prominent propellant oxidizers and fuels are considered with the aim of providing a groundwork for a subsequent qualitative analysis. Every chemical is treated independently and examined throughout its' life cycle ***as a rocket propellant***. This cycle has been previously bulleted, and each subsection below directly relates to this list.

1: Raw Materials Sourcing & Storage

LOX

Raw resource gathering is non-existent for liquid oxygen production. The necessary base compound (O_2) is plentiful in the atmosphere. This also means that potential raw resource transportation impact is non-existent IF the propellant is produced in-situ – i.e., at the launch base. The transport impact therefore is considered nullified. Cryogenic storage is addressed in the later points.

LH2

Hydrogen can be generated by a variety of methods, however, here only methanol reforming was considered, with coal and other fossil fuels being taken as energy sources. Methanol itself is usually obtained through a coal-to-methanol production chain, wherein the greatest proportion of Hydrogen's carbon footprint lies.

RP-1

Before RP-1 production can take place, its base resource – crude oil – needs to be excavated. This is mostly obtained by drilling and constructing oil wells on land or oil rigs at sea. The upkeep of the equipment, transportation of extracted materials all result in environmental impact. Estimates for the environmental impact of crude oil gathering and transportation can be obtained using oil manufacturer information.

NTO
Nitrogen Tetroxide is generally produced from Ammonia. Ammonia itself, however, is not a compound practically attainable by raw resource sourcing, and is instead produced by reacting hydrogen and nitrogen via the Haber-Bosch process. Hydrogen for the reaction is produced from hydrocarbons during the steam reforming process, while natural gas, petroleum gas and naphtha are used to produce the nitrogen. As manufacturer data on emissions is unavailable, an approximation was made by summing the GWP of hydrogen and nitrogen production. Ammonia GWP was calculated by using US inventory estimates [9].

UDMH
UDMH raw materials are dimethylamine and suitable nitrosation compounds as well as gaseous hydrogen and a suitable catalyst. There is an alternative method using the Raschig process, and this tends to be more widely used. This involves sodium hypochlorite and ammonia mixtures under various temperatures and pressures with the addition of dimethylamine. We have used this as the basis of our calculations.

HTP
Hydrogen peroxide is manufactured almost exclusively by the anthraquinone process, which was originally developed by BASF in 1939. It begins with the reduction of an anthraquinone (such as 2-ethylanthraquinone or the 2-amyl derivative) to the corresponding anthra-hydroquinone, typically by hydrogenation on a palladium catalyst. In the presence of oxygen, the anthra-hydroquinone then undergoes autoxidation: the hydrogen atoms of the hydroxy groups transfer to the oxygen molecule, to give hydrogen peroxide and regenerating the anthraquinone. Most commercial processes achieve oxidation by bubbling compressed air through a solution of the anthra-hydroquinone, with the hydrogen peroxide then extracted from the solution and the anthraquinone recycled back for successive cycles of hydrogenation and oxidation. The figures for raw material CO_2 per kilo of HTP are available.

APCP
Raw materials for APCP are primarily ammonia and perchloric acid and these have been used as the basis to determine a CO_2 equivalent.

2: Production & Processing

LOX
Liquid oxygen can be produced by a variety of methods but only the cryogenic distillation method is of concern to us as it is the commercial method which can produce large enough quantities with high purity. The greatest source of CO_2 emissions from liquid oxygen production stems from the energy intensive nature of the process. Cryogenic processes have seen improvements in heat-integration to reduce and minimize the use of external utilities but the emissions are still noticeable. Having taken a variety of industry-level liquid oxygen plants, we get the energy requirement of 4.96 kWh/kg LOx. The energy carbon footprint itself depends on the quality of the energy grid: reliance on fossil fuels means higher carbon footprint, while the influence of green and atomic energy sources results in its reduction. A mean value for the global energy carbon footprint was taken.

LH2
Liquid hydrogen is produced by a variety of processes, although the only one relevant to current-day large-scale production is steam methane reforming. The process itself results in an endothermic reaction. As such, generation of energy used in the process has an impact on the emissions. The greatest contributor to emissions is the formation of CO in the chemical reaction during the production of H_2 from methane and water.

RP-1
Refined Petroleum-1 is produced in large quantities by the oil industry. Crude oil is exploited, refined into kerosene and further distilled into RP-1. Well-to-tank kerosene carbon intensity estimates were taken from the industry. The average value was then used to approximate emissions.

HTP
High-test peroxide is produced in high volumes by producing hydrogen peroxide and vacuum distilling the dilute solution to give the required concentration. The main stages are hydrogenation of an anthraquinone followed by oxidation and a subsequent extraction of hydrogen peroxide solution. The solution is then purified and concentrated.

NTO
Nitrogen tetroxide is produced by catalytic oxidation of ammonia, whose emissions impact was approximated in the raw resource gathering section. Catalytic oxidation results in an exothermic reaction, therefore there is a need for supplied energy. We approximated supplied energy impact relative to the global energy grid to determine the CO_2 equivalent.

APCP
Ammonium perchlorate (AP) is produced by the reaction between ammonia and perchloric acid. This process is the main outlet for the industrial production of perchloric acid. The salt can also be produced by salt metathesis reaction of ammonium salts with sodium perchlorate.

UDMH
UDMH can be produced commercially by nitrosation of dimethylamine, to N-nitrosodimethylamine, followed by reduction of the intermediate to UDMH and subsequent purification. UDMH can be prepared, also, by a modification of the Raschig process in which the chloramine intermediate is reacted with dimethylamine rather than with ammonia.

	CO2 kg/ kg Substance	
	Raw Mtl sourcing & Storage	Production
LOx	0	0.96
LH_2	16	6
RP-1	0.48	0.23
NTO	4.77	5
UDMH	19	31
HTP	0.88	18
APCP	8	10

Table 1: Results obtained calculating CO_2 generation during production and processing

3: Combustion

Propellant combustion results in the formation of new chemicals either from the oxidizer-fuel reaction itself or subsequent reactions with the surrounding environment. In order to evaluate their impact on the environment, it is necessary to consider relevant exhaust products. Due to the ever-changing conditions (which depends on factors such as altitude and location) the reaction and its results are never constant. As such, it can be hard to profile an emissions inventory throughout the flight. The majority of emissions species, however, have negligible impact and can be omitted. The relevant emissions can be calculated by respecting the conservation of species. The general method outlined[6,7] was followed, through which individual propellant mixture emission deposition profiles under stoichiometric conditions were approximated.

Carbon Dioxide
Carbon dioxide emissions are primarily a symptom of a carbon-based fuel. During chemical breakdown under combustion, carbon fuel results in carbon oxide (which itself turns into carbon dioxide in a timeframe) and carbon dioxide. This does not happen in non-carbon-based fuels.

Black Carbon (BC) Soot
Just like carbon dioxide, black carbon emissions can be caused by any carbon-based propellant. Black carbon formation in general is the result of incomplete combustion, during which a proportion of carbon is left unused in the oxidation. Due to changing flight conditions, BC emissions are hard to calculate; however, their impact is too significant to ignore. Efforts have been made to estimate carbon soot plume empirically. Ross and Sheaffer (2014), who have studied the global warming potential of BC emissions, have used an approximation of 2% soot mass fraction for Kerosene-based engines; this assumption will be made here. While no research was found on BC emissions in hydrazine-based engines, the calculations followed the approximation by Pradon and Desain [6, 7] - scaled by the reduced mass fraction of carbon loading in the fuel. Cryogenic (LOX and LH_2) and solid propellant configurations are non-carbon, and do not produce black carbon.

Water vapour
Water vapour emissions depend on the propellant mixture in question. All propellant mixtures analysed herein have water as one of the formants during the combustion, except for the solid propellant configuration, which tends to form acids (see Table 6).

Alumina
Alumina, also known as aluminium oxide, is one of the specific emission species of APCP. It forms during solid propellant's decomposition as the oxidizer part (aluminium) reacts with oxygen. Alumina emissions depend primarily on the percentage of aluminium in the solid propellant. 18% was taken for approximation purposes [6]. None of the other propellant mixtures analysed contain any aluminium, and as such are not considered.

Chlorine
Chlorine bonds with hydrogen as hydrochloric acid, is the second emission species dominating the APCP exhaust. Similar to alumina, it depends on the mass proportion of ammonium perchlorate, which acts as the propellant's primary oxidizer. 70% was taken as the proportion of ammonium perchlorate in the propellant mixture [6].

CO2 emissions per kg propellant burned				
LOx / RP-1	NTO / UDMH	HTP / RP-1	LOx / LH_2	APCP
0.88	0.51	0.49	0	0

Black Carbon emissions per kg propellant burned				
LOx / RP-1	NTO / UDMH	HTP / RP-1	LOx / LH_2	APCP
0.02	0.012	0.02	0	0

H20 emissions per kg propellant burned				
LOx / RP-1	NTO / UDMH	HTP / RP-1	LOx / LH_2	APCP
0.243	0.421	0.393	5.143	0

Alumina emissions per kg propellant burned				
LOx / RP-1	NTO / UDMH	HTP / RP-1	LOx / LH_2	APCP
0	0	0	0	0.34

HCL emissions per kg propellant burned				
LOx / RP-1	NTO / UDMH	HTP / RP-1	LOx / LH_2	APCP
0	0	0	0	0.217

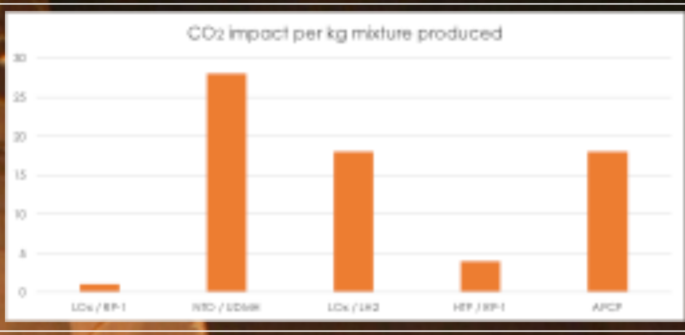
Tables 2 to 6: By-product emissions (in Kg) per Kg of propellant mix burned.

Results

The results are generated by respecting the influence of every part of its life-cycle described previously, giving a “cumulative life-cycle impact”.

Manufacturing emissions

As was shown in the analysis, global warming impact from manufacturing is noticeable for certain oxidizers and fuels. This is best illustrated in graphical format, as shown in Figure 2 opposite which presents the quantity of CO_2 emissions generated for every Kg of propellant produced.



Combustion emissions

CO₂ equivalent for combustion by-products					
CO_2	Black C	H_2O	NO_x	Al_2O_3	HCL
1	830	0	0	-77	1

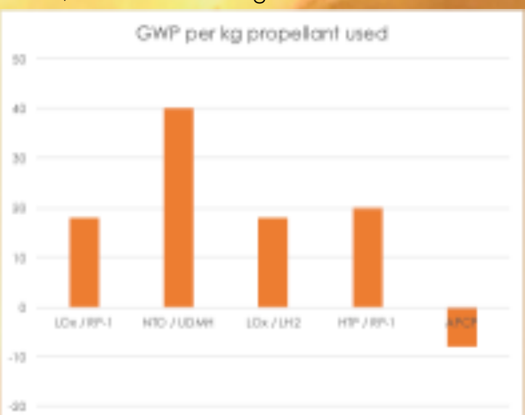
The biggest propellant environmental impact is the global warming impact. Every stage from cradle-to-grave has been shown to result in emissions. In order to objectively quantify the total global warming impact, we utilise the notion of CO_2 equivalent emissions. It converts the emissions impact of 1 kg of a particular species of emission to CO_2 equivalent emissions that result in the same global warming impact. The approximations of specific CO_2 equivalent data for each species of emissions are illustrated in the table shown.

Total combustion CO2Eq

Taking all the combustion profiles and conversion of particular emission species into a comparative form gives us the approximation of global warming impact resulting from a combustion of 1 kg of a particular propellant configuration in terms of CO_2eq. It can be seen that Kerosene-based propellant mixtures result in the highest CO_2 equivalent emissions. Carbon mass fraction in Hydrazine is smaller, and therefore its emissions are also smaller. Cryogenic propellant configurations (LOX LH_2) results in no global warming impact during combustion. APCP, whose alumina emissions result in **cooling,** as opposed to warming, result in an overall cooling impact.

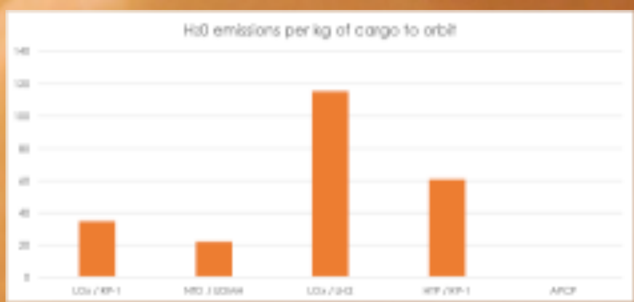
Total global warming potential

Considered together, manufacturing and combustion findings give the total global warming potential (GWP) per 1kg of propellant used, illustrated in the figure below.



Water vapour emissions

Water vapour emissions also contribute to global warming due to the ability of the vapour to absorb heat. As such, it is important to consider the amount of H_2O generated during the combustion phase that will be present in the stratosphere and above. As a secondary effect, water emissions also result in the formation of mesopheric clouds - a secondary effect which, importantly, is not present in other emission types

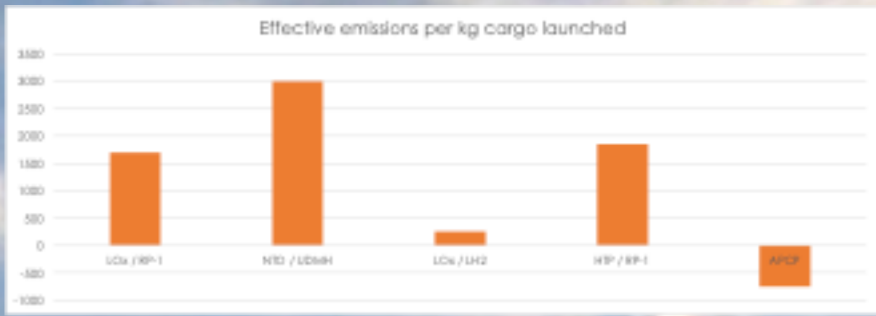


Proxy Mission

Global warming impact of both manufacturing and combustion of chosen propellant mixtures has been conducted. In order to give the best possible comparison of the propellant combinations, a proxy launcher mission was designed with the objective of placing a 300kg payload into sun-synchronous orbit. This is particularly relevant since different propellant combinations will lead to different rocket designs; an obvious example is the size required for an LH_2 tank compared to RP-1. IF LH_2 had been used for the first stage of the Saturn-V launch vehicle, the resulting stack would have been over 400 feet tall as compared to the ~365-foot flight configuration. This would have also resulted in a significant extra mass for the lower stage.

As such, looking at CO_2 equivalent emissions per kg of propellant does not tell the whole story.

Using this approach, it is immediately apparent that the LOx LH_2 combination is most effective – but the trade-off is the large volume of water vapour and its potential for global warming.



Conclusions & Recommendations

It is clear from our research that we have only just begun to scratch the surface of the impact of propellants, from raw materials to launch, on global warming and, indeed, on the atmosphere as a whole. There are other propellant combinations, including hybrids, that should undergo rigorous scrutiny for CO_2, H_2O and black carbon emissions. Potential production of CFCs must also be considered, and any free-radical generation in the upper atmosphere that could lead to ozone depleting potential.

Up to now, the number of launches per year has probably had a negligible impact on global warming, but we are seeing an almost exponential increase in launch cadence, not only from the large primes that are already flying, such as SpaceX, but in the plans of those to come. We must take into account the incredible number of small orbital AND sub-orbital vehicles that will be making their debuts over the next 12 – 24 months and whose very existence depends on a large numbers of launches per year in order to generate sustainable revenues.

Given the many ways of "determining" atmospheric impacts, it is imperative that a standard methodology is quickly established in order to be able to fully categorise and compare existing and emerging launchers. This will also enable us to see through a lot of "greenwashing" claims made about propellants and launch vehicles where unrealistic, non-like-for-like comparisons and statements are being casually thrown into the mix.

This may simply be, in the first instance, a kg CO_2 equivalent/kg payload to a fixed orbit, but must quickly encompass H_2O vapour, CFC output, and black carbon output.

What is important is that we do not ignore the contribution that the global launch industry makes to atmospheric pollution and global warming. Moreover, whilst we have literally tens of new launchers coming onto the market, each should be scrutinised for its' green credentials in order to remove "Cheap but dirty" combinations. We should, in effect, endeavour to be 'near zero by design' from the outset.

To facilitate this, a comprehensive database of all propellants must be compiled with their atmospheric contributions, to give launch vehicle manufacturers (and customers) the best information to select the best propellants for the job, whilst minimising environmental impacts.

We must not delay this important work – given the obviousness of global warming, we ignore this at our peril.

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Space for the next generation

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The UK Space Sector has a well-established track-record in propellants and propulsion R&D and this work contributes to the as-yet poorly understood area of propellant and propulsion environmental and climatic effects.

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