JOURNAL OF
EMERGING INVESTIGATORS

Article

What is the optimal fuel for space flight? Efficiency, cost, and environmental impact

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SUMMARY

The space flight industry is growing rapidly. In order to increase its efficiency and ensure sustainability as the industry continues to expand, the present study investigated and compared a set of rocket propellants to determine the most and least advantageous fuels to use going forward. Chemical properties, production and storage cost, and environmental impact were the factors considered. We hypothesized that the propellants currently used the most in terms of launch frequency, i.e., RP-1 (kerosene) and hydrazine, would perform best in our comparison. To compare various properties, we derived three novel equations, providing numerical, objectively comparable values for each considered fuel in terms of its economic, environmental, and efficiency potential, equally weighed. Results showed ammonium dinitramide (ADN)-based propellants, Al/Ice, and liquid methane are the most optimal fuels, with hydrazine, liquid hydrogen, and nuclear thermal propulsion (NTP) being the least optimal out of the nine fuels compared. In conclusion, we challenged the hypothesis and formed a recommendation on further research and potential implementation of novel and less-used fuels mentioned above, which should be pursued as a priority, to ensure a sustainable future for the space industry and the planet as a whole.

INTRODUCTION

In the 20th century, the space industry was dominated by developed countries, especially the United States of America (USA) and Union of Soviet Socialist Republics (USSR) (1). However, with the emergence of satellite sensing and communications used for weather forecasting, television, internet, and the global positioning system (GPS), many new countries and entrepreneurs began to see the economic potential of, and thus invest in, the space industry.

In the year 2021, 135 orbital rockets were successfully launched, which shows a 39% increase when compared to the 97 launches in 2019 (2). There are also currently 4,852 active satellites in orbit as of December 31, 2021, presenting a 119% rise compared to the 2,218 active satellites on December 19, 2019 (3). Focusing on environmentally friendly progress will help reduce the contribution of the space industry to climate, since despite there being around 320,000 times as many airplane flights as rocket launches in a year, a long-haul airplane flight emits 1-3 tons of CO_2 per passenger, whereas one space flight releases 50-100 tons per passenger or around 27 tons for every ton of payload (4).

The environmental footprint and cost of each launch is heavily impacted by the propellant being used, which is why this paper focuses on comparing different propellants and analyzing their impact on the rocket launch success. For example, using a more energy-dense fuel and a more energy-efficient rocket engine would reduce the amount of fuel needed for each mission, conserving resources, reducing the cost, and improving productivity (5).

Improving technology and processes associated with fuel production in turn will make space flight more affordable for private businesses and developing countries. Only ten countries have so far achieved independent orbital spacecraft launch capability, and only seven currently retain it (1). Lowering launching cost to allow more countries to enter the market, can be achieved through building reusable rockets, funding research of novel technology, and increasing production scale (while retaining quality). As a result, such market expansion will lead to greater international collaboration and important innovation in the field.

In order to address the highlighted goals in as objective a way as possible, we developed quantitative metrics in the areas of energy efficiency, financial viability, and environmental impact to provide direct comparison between spacecraft fuels and determine examples showing the greatest potential for future research in context of widespread application for sustainable development.

Impulse per unit of weight of fuel combusted is the specific impulse, I_{sp}, and the impulse per unit of volume of fuel burned is the volumetric impulse. The reason a fuel's potential energy is most commonly referred to in terms of specific impulse, is because of how important mass is when it comes to launching rockets. Every extra kilogram of load costs extra fuel to lift it up, and that fuel also needs fuel to lift it up. As a result, the vast majority of a rocket's weight is its fuel, an example being the Soyuz rocket, 91% of its weight being kerosene (6). Volume of the propellant is also important because the less dense it is, the bigger the storage tanks and thus the bigger the rocket must be. Larger rockets have greater surface area, meaning that they experience more air resistance during launch, which increases the fuel required to reach orbital or escape velocity. Furthermore, larger tanks need to be thicker to maintain and withstand the propellant's pressure, increasing the rocket's weight. Consequently, fuel density values were one of the main aspects considered during initial propellant selection process.

Different propellants are appropriate for different missions and for distinct stages within one mission. First stages (such as thrusters) need to be equipped with a propellant that can release enormous amounts of energy in short periods of time in order to overcome the Earth's gravitational pull, whereas stages travelling through space (in a vacuum) may have fuels

DOI: https://doi.org/10.59720/22-238

releasing energy more slowly and controlled since their priority is energy efficiency rather than energy density. As the first stages require the most energy to escape the atmosphere, they currently need the most fuel. An example is the Falcon 9 rocket, which has 395,700 kg of propellant in its first stage out of the total 488,370 kg it carries - 81% of its total fuel capacity (7). It might seem logical because the Falcon 9 is not used for missions that travel far from the Earth, so provided is another example: The Apollo 11 mission's Saturn V rocket's first stage carried 55% of the total fuel, which was 521,400 out of 947,459 gallons total. Although this paper acknowledges that rockets of future missions might need more fuel in later stages due to increasing flight distance, it is also recognized that travelling through space requires less volume of and lower energy output rates of fuel, increasing the choice range of fuel for later stages. Furthermore, unlike the first stage, exhaust gases from subsequent stages will not be released in the Earth's atmosphere, reducing its potential impact. Based on that, it was concluded that finding a pertinent fuel for the first rocket stage is the primary goal, and thus the focus of this paper.

Based on background information and educated assumptions, we hypothesized that the propellants likely to perform best in comparison were those that are in most widespread current usage, in terms of frequency of launches. The most frequently flown rockets in Q1 and Q2 of 2022 were SpaceX's Falcon 9 and China's Long March, which use RP-1 and hydrazine fuels, respectively (1). Therefore, we predicted that those fuels would be ranked highest, whereas fuels such as Ammonium Dinitramide (ADN) and Al/Ice, which are

Propellant name	SI at sea level s	Density g/cm^3	Combustion temp K	Source
Ion thruster	4190	n/a	n/a	(12)
Metallic hydrogen+LOX	1700	0.70	6700	(9)
Metallic hydrogen diluted	1030	0.70	3500-3800	(9)
Nuclear Thermal rocket (NTP)	900	0.07 (H_2)	n/a	(13)
Liquid hydrogen + LOX	390	0.07 / 1.14	2985	(14)
Liquid methane + LOX	299	0.42	2000	(15)
Ammonia + LOX	294	0.89	3090	(14)
RP-1 + LOX	289	0.81-1.02 / 1.14	3670	(15,19)
N_2O_2 + UDMH	285	1.45 / 0.79	3415	(16)
ADN	275	1.81	423-483	(20)
PMMA	250	~1.18	523-623	(24)
Perfluoro-type e.g. perfluorobutane	250	1.59	n/a	(21-23)
Polyethylene (PE)	244	0.95-0.97	622	(27)
Oxygen-hydrazine	234	1.14 / 1	297-543	(29)
Paraffin wax	230	~0.90	472	(30,32)
Paraffin + HTPB (1:1)	225	0.91	n/a	(28)
APCP	210	varies	varies	(35)
Nitropolymer ammonium nitrate	210	1.72	503	(35)
HTPB + nitrous oxide	204	0.92	930-1190	(38)

Key: light blue = liquid, grey = solid, yellow = hybrid; magenta = unimplemented / future propellants.
Sorted in order of decreasing specific impulse.
n/a – Data not available - Missing values due to lack of publicly-available data or inapplicability of those properties to the fuel.
Multiple values given where sources disagree.

Table 1: Summary data for 23 initially chosen propellants.

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fuel	I_{sp} s	density g/cm^3	density kg/m^3	volumetric I_{sp} s/kg	Emissions /mol	GWP /100y	LD50 mg/kg	Source
Metallic hydrogen	1400	0.70	700	980000	H_2O	0.005	n/a	(9)
NTP (with H)	900	0.07	70	63000	H_2	5.8	114	(40,41)
Liquid hydrogen	390	0.07	70	27300	H_2O	0.005		(39)
Methane	360	1.14	1140	410400	CO_2 + $2H_2O$	1.005	57115	(49)
Kerosene (RP-1)	289	0.92	915	264435	$12CO_2$ + $13H_2O$	12	7000	(18)
ADN	275	1.81	1810	497750	N_2 + O_2 + H_2O	0.005		(39)
Aluminium (Alice)	275	1.81	1808	497310	Al_2O_3 + $3H_2$	5.8		(40)
Hydrazine	292	1.00	1000	234000	NH_3 + N_2 + H_2	5.8	140	(43, 40)
HTPB	204	0.92	920	187772	$0.7C_4H_3$ + $0.3C_2H_4$	0	34600	(48)

LD50 omitted for non-toxic propellants.
n/a – data not available

Table 2: Properties of downselected propellants.

largely unknown, would perform worse. However, our results showed ADN based propellants, Al/Ice, and liquid methane to be the most optimal, with hydrazine, liquid hydrogen, and NTP (nuclear thermal propulsion) being the least optimal, out of the 9 fuels chosen and compared. In conclusion, the initial hypothesis was challenged, leading to the recommendation that further research for potential implementation of specific novel and less-used fuels should be pursued as a priority, to ensure a sustainable future for the space industry and the planet.

RESULTS

In order to research and analyze a variety of rocket propellants with the goal of identifying fuel most deserving of further research in the context of large scale application, we filtered the initial wide list of fuels by considering how widespread a given propellant is, its specific impulse value, density, and its environmental impact **(Tables 1 and 2)**. Then we conducted a second, more in-depth round of analysis, applying the energy, cost, and harm metrics to the shortlisted propellants **(Figure 1)**. The equations include: the energy equation or combined impulse, obtained via the mean of specific and volumetric impulse; the cost equation, which added the price of fuel to its storage, with consideration of special storage requirements such as density and temperature, and thus possible maintenance and handling premiums; and the harm equation, incorporating the weighted global warming potential of emissions multiplied by the acute chemical toxicity of the fuel.

While doing research to form the initial list of fuels for this study, the question of "why aren't shorter chain hydrocarbons used as fuel?" arose, considering hydrocarbons are the most used fuels worldwide today (8). They burn more efficiently and are easier to ignite, so it could be advantageous to replace kerosene with a short chain hydrocarbon that is liquid at room temperature. Since this conclusion could impact the research by introducing a new potential fuel, a decision was made to analyze this further. For that, an energy balance calculation was made for kerosene and pentane (the shortest chain hydrocarbon liquid at room temperature), calculating and comparing their enthalpy of reaction **(Tables 4 and 5)**.

The results demonstrate that pentane releases 2.4% more energy during combustion. Based on this, we concluded that this relatively small energy advantage does not outweigh the drawbacks of higher cost associated with shorter hydrocarbon chains, as well as extra energy needed to keep it in liquid state while in the cold temperature of space vacuum. Therefore, other hydrocarbons apart from kerosene did not enter the scope of this paper.

Using several physical and chemical properties of the fuel as input, we used harm, energy, and cost equations to evaluate the usefulness of each fuel **(Tables 2 and 3)**. For each fuel, we calculated a value that corresponds to its economic (monetary) advantage, environmental friendliness, and energetic potential relative to other fuels. To aid visual interpretation, the data was normalized and plotted on a bar

DOI: https://doi.org/10.59720/22-238

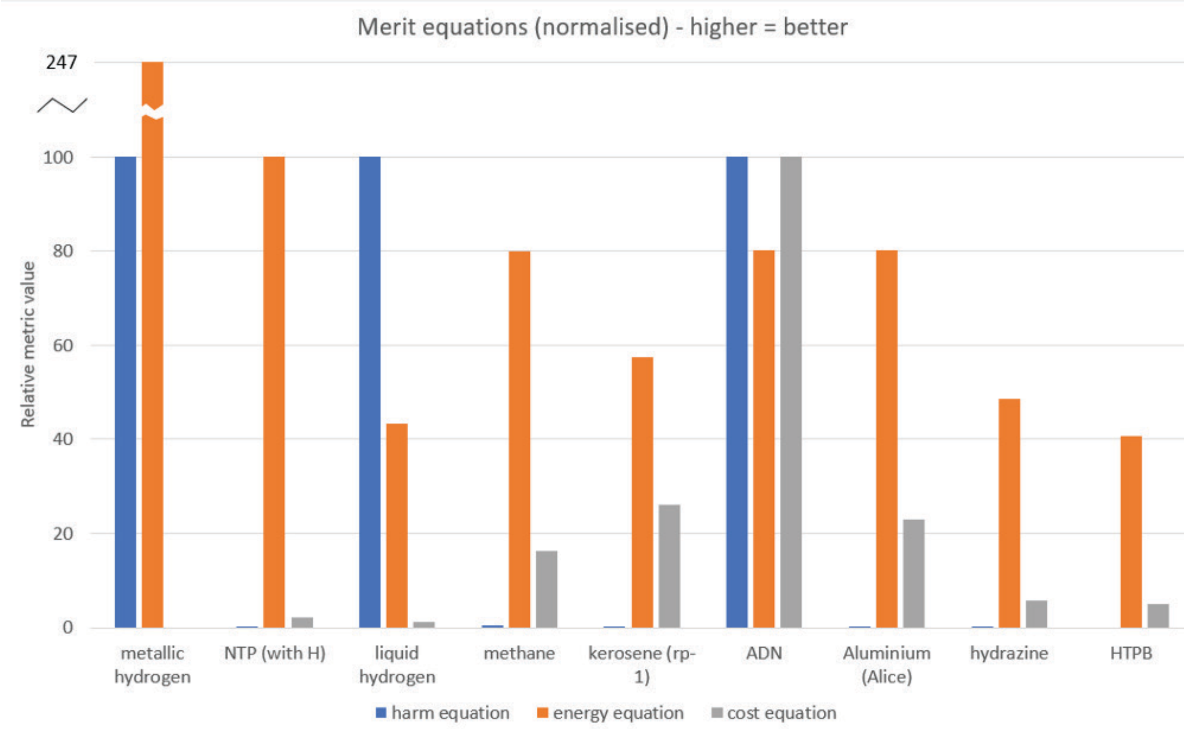

Figure 1: Normalized merit metrics.
Harm and cost values reciprocated, so higher = better for all metrics.
Harm and cost normalized to highest value = 100, energy normalized to NTP = 100 for readability.

fuel/property	harm score	energy score	cost score
metallic hydrogen	0.005	1,445.00	-
NTP (with H)	34.8	481.50	26.64
liquid hydrogen	0.005	209.38	46.13
methane	1.01	247.72	3.69
kerosene (rp-1)	12.065	276.72	2.29
ADN	0.015	435.55	0.60
Aluminum (Alice)	5.8	290.67	2.60
hydrazine	52.2	292.00	10.39
HTPB	0	195.84	11.96

Table 3: Combined and color-coded harm, energy, and cost metrics.
Green=best, red=worst.

graph **(Table 3, Figure 1)**. These calculations showed the relative advantages and disadvantages of each propellant in terms of those three categories. Ranking of each fuel was based on the number of categories in which the fuel showed precedence, how significant was the lead compared to the average, and the relative significance of drawbacks in categories where the fuel was weaker.

In the environmental harm section, metallic and liquid hydrogen, as well as HTPB performed best, attaining scores of 0.005 or lower **(Table 3)**. It is apparent that the high lethality and GWP (global warming potential) of some fuels and the benign nature of others created highly contrasting values for the harm metric, resulting in differences of several orders of magnitude.

In the energy section NTP, ADN, and metallic hydrogen showed clear precedence with scores of 481, 435, and 1445 respectively **(Table 3)**. Finally, in the cost metric the fuel attaining the lowest and thus best score (0.6) was ADN, along the score range of 45.47. Overall, the propellant which performed best in all the presented categories was ADN **(Figure 1)**. By contrast, the fuels which generally performed the worst were hydrazine and liquid hydrogen, showing values significantly worse than average in the 3 categories.

DISCUSSION

By surveying and analyzing the results of the energy, cost, and harm equations it can be derived that some of the most widespread rocket fuels used today may be less advantageous than other less used propellants they were compared to, based on the comparison criteria, although it is important to note that these conclusions should be taken in comparatively, rather than arbitrarily.

According to our results, hydrazine and liquid hydrogen appear to have the worst scoring parameters. Hydrazine,

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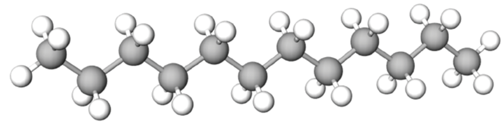
Average Molecular formula $C_{12}H_{26}$	
Combustion reaction $2\ C_{12}H_{26\ (l)} + 37\ O_{2\ (g)}$ $\rightarrow 24\ CO_{2\ (g)} + 26\ H_2O_{\ (g)}$	
Reactant bond energies 11 C-C 348 kJ/mol 26 C-H 412 kJ/mol	11 x 348 + 26 x 412 = **14 540 kJ/mol**
Product bond energies 48 C=O 743 kJ/mol 52 H-O 463 kJ/mol	(48 x 743 + 52 x 463) /2 = **29 870 kJ/mol**
Energy released	29 870 - 14 540 = **14 540 kJ/mol**
Specific energy of combustion m_r = 170 g/mol 1000/170 x 15330 = **<u>90 176 kJ/kg</u>**	

Table 4: Enthalpy analysis of the combustion of kerosene.

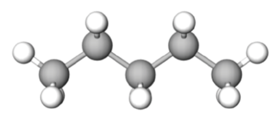
Molecular formula C_5H_{12}	
Combustion reaction $C_5H_{12\ (l)} + 8\ O_{2\ (g)}$ $\rightarrow 5\ CO_{2\ (g)} + 6\ H_2O_{\ (g)}$	
Reactant bond energies 4 C-C 348 kJ/mol 12 C-H 412 kJ/mol	4 x 348 + 12 x 412 = **6 336 kJ/mol**
Product bond energies 10 C=O 743 kJ/mol 12 H-O 463 kJ/mol	10 x 743 + 12 x 463) /2 = **12 986 kJ/mol**
Energy released	12 986 – 6 336 **6 650 kJ/mol**
Specific energy of combustion m_r = 72 g/mol 1000/72 x 6650 = **<u>92 361 kJ/kg</u>**	

Table 5: Enthalpy analysis of the combustion of pentane.

although commonly used in thrusters, has limited energy potential and is highly harmful as well as expensive. Liquid hydrogen presents minimal harm to the environment but lacks energy potential due to its drastically low density impacting its high cost. Lower density fuel requires larger tanks to store the same amount of impulse's worth as for more dense fuels. Another fuel of note is NTP, which despite technically using hydrogen as fuel in the system, converts energy more efficiently, making its energy potential comparatively high. Its drawbacks are the prohibitive cost (caused mainly by hydrogen's low density) and potential risks in production and usage due to radioactive nature of the nuclear power.

Kerosene as a fuel source is advantageously cheap and average in terms of energy potential but it causes major environmental impacts due to its release of black carbon (BC) during combustion. BC not only contributes to climate change, but also causes significant health risks upon inhalation, such as respiratory and cardiovascular diseases, and cancer (8). Therefore, we suggest kerosene should be used to a lesser extent and replaced by more environmentally neutral options with good performance.

Apart from fuels that represent the industry today, the compared list also included propellants that are either not possible to use with current technology, are still under research and development, and/or not widespread. Our results clearly show that metallic hydrogen is a prospective fuel worth investigating further. It eliminates the major drawback of using liquid hydrogen - its low density - and thus has the potential to be a highly energy-dense fuel (almost three times more than the highest-energy modern fuels), while remaining harmless to the environment. Its main drawback is the potentially unviable high price it will have because its production will require an exceedingly high pressure (400-500 GPa), as it has not yet been successfully manufactured

DOI: https://doi.org/10.59720/22-238

to this day (9). Another fuel to point out as a research target is ADN. ADN based propellants need further research because they have not entered the field yet, despite having favorable characteristics.

One of the likeliest reasons for why propellants like ADN are not used in place of LH is due to limitations in technological advancement. LH was first used in an internal combustion engine in 1804, whereas ADN for example, was only invented in 1971, with US gaining first access to it in 1989 (10). So far there have not been developments in infrastructure for ADN's industrial-scale production, which is a significantly more complicated process than LH synthesis.

Overall, some of our results were rather unexpected. LH is a very widespread fuel that is considered remarkably effective due to the comparatively high I_{sp} and lack of greenhouse gas emissions, but it has a significant drawback of low density, which is not often mentioned. This fact shows how important it is to make decisions based on in-depth analysis covering all factors that can present an impact. On the other hand, there is ADN, which presents favorable characteristics and is available to produce with current resources yet is not used in the industry today. This shows that there is room for improvement to how the space industry works right now, in all the three aspects of sustainability, energy efficiency, and economic viability.

The depth of data analysis in this paper necessitated a smaller range of propellants to be compared. This means that the industry may not have been represented fairly, as there are a lot of fuels remaining that have not been mentioned, which are potentially better options than the ones derived in the discussion. As this study involved gathering a large amount of data, we could not present all desired information in the mentioned tables, either due to lack of available sources or specifics of certain fuels which limits our knowledge on their properties. Decision making as to the composition and balance of elements in the equations is dependent on context, and if this approach is to be applied to specific applications, or in areas at particular risk, future use may justify amendment or inclusion of additional factors.

Future work may cover a broader range of fuels and consider indirect emissions as well as direct ones, in order to mitigate the limitations listed above. If the results are supported by other studies, a policy-focused approach should be taken in order to encourage public and private companies to follow the advice presented.

MATERIALS AND METHODS

To obtain an objective and thorough analysis of current and potential rocket fuels a range of fuels were chosen and compared. This was done using a set of factors that provide numerical properties to describe the fuels in an objective way. Initially, a top-level list of fuels was chosen to represent what is used in the industry today and were compared by their inherent properties. Subsequently, a selection criterion was established and implemented, narrowing down the initial 23 fuels to 8, which were then thoroughly analyzed by a wider range of factors to discuss in a more nuanced fashion, and conclude which one is the optimal fuel for space flight.

Fuel Selection Process

As it was unviable to analyze all fuels that are currently used globally, a range of 23 fuels was selected to represent the industry. Out of an initial list of fuels widespread enough to have sufficient detail available in the public domain, the list had to be narrowed down further in order to permit an analysis of sufficient depth, so the focus lay on the most in demand or the most promising rocket propellants.

To select the right fuels for comparison, it was essential to consider how widespread the fuel currently is, in order to provide contextual information to determine the potential benefits of replacing a fuel in current use, as well as providing readily available options for that replacement. The more widespread a fuel is, the bigger the opportunities for potential impact yet also the bigger the challenges for adoption if the fuel is replaced. Further, fuels that are not currently used (e.g., due to technical difficulties, such as storage, production expense, or lack of technological development) were also considered; however, a different approach was implemented to account for those circumstances.

A variety of currently used or potentially usable fuels from the three types (liquid, solid, and hybrid) were picked for initial comparison and further down-selection. Their basic properties were obtained from literature: specific impulse I_{sp} (s) at sea level, density ρ (g/cm^3), combustion temperature T (K), and wholesale purchase price ($/kg). The products of their combustion were also reviewed for environmental impact **(Table 2)**.

To select a smaller subset of fuels for comparison, three criteria were used. The first is how widespread that fuel currently is in the industry. Authoritative sources for this are challenging to locate and validate, due to the proprietary nature of current, increasingly commercially led space flight, but it can be estimated by finding the rockets flown most frequently each year and the fuel those rockets use. For a fuel to fit the category of "widespread" it had to be one of the five most used fuels. For the purposes of this a logical assumption was made, that a narrow number of the most used fuels (such as 5) would compose a large fraction of the total fuel use (~70-80+%) in the industry.

The second factor used to aid the selection process was the I_{sp} of the fuel. For a fuel to fit the category of "high impulse", it needed to be over 280 s of specific impulse or over 400 s of volumetric impulse at sea level. This allows them to be in the top 30% by impulse out of all propellants in the initial list.

The third factor was the consideration of a fuel's combustion emissions. For the fuel to fit the category of "low impact," its complete combustion products must not contain any greenhouse gases or somehow toxic or harmful substances either to humans or the environment. This factor was picked because recent trends in global warming are making humanity prioritize hindering and reversing its effects, mostly by reducing harmful emissions from fuel combustion.

The fuels from the initial list that fit at least two out of the three previously mentioned criteria or have substantial potential to fit them were selected for the in-depth comparison. The completed list of propellants which will be compared and evaluated in this research is as follows: Liquid hydrogen (will be further referred to as LH), kerosene (specifically RP-1), ADN, methane, HTPB, Al/Ice, hydrazine, and metallic hydrogen. A total of 8.

Comparison Criteria

In order to compare the selected subset of fuels, a range of criteria were shortlisted. These included specific impulse,

DOI: https://doi.org/10.59720/22-238

volumetric impulse, production cost, density, combustion temperature, required storage pressure, required storage temperature, mass of harmful emissions during production and combustion, severity of harm posed by emissions, and toxicity of fuel. To reduce the number of factors used for comparison and therefore simplify the analysis process, 3 compound factors were created. They represent all the variables listed above, grouped together to provide a numerical value in the 3 categories: energy they provide, environmental harm they pose, and economic viability.

The first factor is referred to as the *energy equation*. To calculate it, specific impulse I_{sp} and density ρ were multiplied together to get volumetric impulse and the resultant value was averaged with specific impulse to obtain combined impulse.

Combined impulse I_c is therefore given by equation 1:

$$I_c = \frac{\rho I_{sp} + I_{sp}}{2} = \frac{I_{sp}(\rho + 1)}{2}$$

Where I_{sp} is the specific impulse, and ρ is density. By taking the average of both impulses, both specific and volumetric impulses were given equal weight, because they were deemed to have an equally significant impact on a fuel's efficiency: greater specific impulse reduces the weight of fuel the spacecraft has to carry, thus decreasing fuel cost and total emissions volume, whereas a greater volumetric impulse facilitates smaller tanks, reducing the mass and surface area of the spacecraft to further decrease the required amount of fuel required for its flight, and thus the costs and emissions volume.

The second factor derived was the cost equation, combining the cost of producing and storing equivalent of 1000 s of impulse of each fuel:

Cost C is therefore given by equation 2:

$$C = C_f + C_t$$

where C_f is the cost of fuel per kilogram in US dollars, and C_t is the cost of a storage tank that can store a quantity of fuel that can produce 1000 s of impulse.

By adding the cost of storing 1000 s (instead of 1 kg) worth of specific impulse, the energy density of the fuel, as well as temperature and pressure of storing it were automatically taken into account. The calculation included determining the price of a normal tank in comparison to a cryogenic one, which is required for liquid fuels that would be gaseous at room temperature. The price of 1 m^3 in each of the tanks was then calculated and used to determine how many cubic meters are needed to store a specific amount of energy. This is not double consideration of the density property of a fuel even though it was utilized in the impulse equation earlier because the former equation surveys how density affects the propellant's energy output, whereas here the focus lay on a tank's size (and therefore price), as a factor of the fuel's density.

The final factor is the impact equation. Impact (or 'harm'), H was calculated using equation 3:

$$H = \sum_{i=1}^{n} (m_i G_i)\, L$$

where n is the number of different combustion products to be accounted for, m is the number of molecules of each product produced per molecule of reactant, and G is the GWP_{100}, i.e. the global warming potential over 100 years of each product, as compared to the GWP_{100} of CO_2, which has the normalized GWP_{100} value of 1 here, and L is the LC50; the lethal dose per kg of body weight that would be fatal to 50% of subjects that ingested it.

When using the LC 50 in the calculation, the numerical value was turned into a ranking of how hazardous the substance is. The rank distribution was based off the acute toxicity classification from the Globally Harmonized System (GHS) (11). This was necessary because using the LC50 value directly would have caused confusion in the results, due to the large disparity in the values as well as the fact that a bigger LC50 value constitutes less toxicity.

The reason the fuel's lethality value was accounted for despite the statistical rarity of fuel-leakage related accidents, is due to the significantly increased precaution procedures and equipment required to handle more toxic fuels. Fuels with higher toxicity values are also more likely to produce harmful by-products that don't possess significant global warming potential but may be detrimental for human health or other life forms in the ecosystems they escape to. For example, carcinogenic and mutagenic nature of hydrazine fuel and kerosene's combustion products causes harmful genetic mutations such as cancer in humans and other animals.

Received: October 3, 2022
Accepted: March 31, 2023
Published: December 28, 2023

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