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# Review and Perspectives of "Green" Self-Pressurizing Propellants for In-Space Propulsion and their Applicability to Orbital Stages

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**Green Propulsion is an increasingly prevalent trend in the space industry that has experienced significant growth in recent decades. The shared objective of researchers is to identify suitable alternatives to existing liquid propellants for space applications, which are toxic and difficult to manage during ground operations. Research and industry have explored a wide range of options and, especially in the last few years, there has been a clear push from the market and the overall space sector to utilize cheaper and simpler systems.**

**Numerous alternatives are emerging as advantageous for a variety of applications. Green propellants are typically utilized for in-space propulsion applications that necessitate high thrust and short transfer durations and over the years, around the world, researchers and industries have tested dozens of different propellants. Recently there is an increased interest in exploiting a particular characteristic of some compounds, the so-called self-pressurization, i.e. the property of compounds with a high vapor pressure at conventional operating temperatures of possessing an inherent feeding pressure. The principal advantage of systems based on these propellants is their self-pressurizing capability, which eliminates the need for external pressurization sub-systems, resulting in simpler and more compact designs.**

**The present study evaluates the relative performance of many of these compounds as propellants for an Orbital Stage reference scenario.**

## I. Nomenclature

| | |
|---|---|
| ATC | Acute Toxicity Classification |
| ECHA | European Chemicals Agency |
| EM | Equilibrium Model |
| GEO | Geostationary Earth Orbit |
| GTO | Geostationary Transfer Orbit |
| HEM | Homogeneous Equilibrium Model |
| LEO | Low Earth Orbit |
| MMH | Monomethyl Hydrazine |
| NTO | Nitrous Tetroxide |
| OTV | Orbital Transfer Vehicle |
| REACH | Registration, Evaluation, Authorization, and Restriction of Chemicals |
| SPC | Single Phase Compressible |
| SPI | Single Phase Incompressible |
| SVHC | Substances of Very High Concern |
| UDMH | Unsymmetrical Dimethyl Hydrazine |
| $I_{sp}$ | Specific Impulse |
| *O/F* | Oxidizer to Fuel ratio inside the combustion chamber |
| $P_V$ | Vapor Pressure |

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| | |
|---|---|
| $T_C$ | Combustion Temperature |
| $\Delta V$ | Change of velocity required for orbit change/orbit maintenance |
| $\rho$ | Density |
| $\rho I_{sp}$ | Volumetric Specific Impulse |

## II. Introduction

The study analyses the utilization of a specific class of compounds for their use as rocket propellants for in-space applications, and in particular for Orbital Transfer Vehicles (OTVs). The focus of the study is on chemical compounds that have a high vapor pressure at conventional operating temperatures, and hence possess an inherent feeding pressure in the pipelines. The property is hereby referred to as self-pressurization. The major promise of such propellants is the possible elimination of external subsystems or devices dedicated at increasing the pressure prior to entry into the combustion chamber, as shown in Figure 1. The resulting systems have reduced complexity, not necessitating of critical and heavy components such as pressurizer tanks and pressure regulators, however related components need additional care, for instance the tanks required to contain these substances become heavier.

The study first introduces the reference scenario, hence the principal requirements of an OTV, to understand where these compounds could benefit and boost new developments. Companies actively pursuing similar developments are outlined, together with their design choices. The investigation then evolves analyzing the properties that are researched in propellants to be considered self-pressurizing and explores the necessary trade-offs that must be carried out in a preliminary design phase regarding the benefits and disadvantages of the various compounds under consideration.

The propellants are initially compared considering both their physical characteristics, including density, vapor pressure, stability, but also compatibility with human interaction without the use of invasive protection devices. The latter feature of propellants is commonly referred to as "green" and its advantages are connected not only to the inherent risk during ground operations, but also to the reduction of associated handling costs. The propellants are further compared against their utilization as rocket propellants, with a particular look at their performance in terms of specific impulse, volumetric specific impulse, and combustion temperature.

Finally, the study explores the current state of the art modeling techniques for such propellants, in particular it describes the commonly models utilized to describe saturated fluids behavior in terms of self-pressurization and mass flow rate. The development and resolution of such models is key to better develop connected technologies, especially for novel applications such as OTVs.

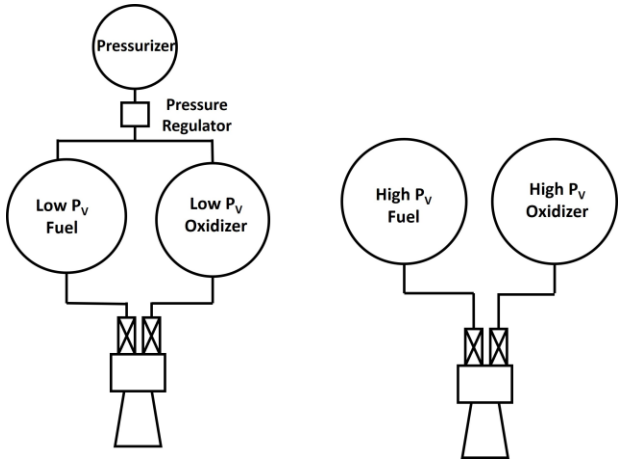


**Figure 1 – Conventional bipropellant pressure-fed architecture (left picture) and self-pressurizing alternative (right picture)**

## III. The Reference Systems

It is useful, for a preliminary overall propulsion system performance estimation and design, to define a reference application scenario. The study is based on a new arising class of Orbital Stages, currently in development by numerous entities around the world, with the multi-faceted purpose of performing a wide spectrum of missions, commonly referred to as In-orbit Servicing (IoS) [1]. Some of such systems are already active, but a greater number

of new devices is currently in different phases of development. Private companies are at the forefront of new developments, with multiple proposed concepts around the world, as shown in Figure 2. Many of these concepts are tailored to specific fields of application, yet they are designed to be adaptable to different missions. Some of these companies are already thriving in the business, and the sector is anticipated to experience substantial growth in the coming decades [2,3]. This growth is expected to be driven by an increased demand for access to new services in space from existing entities and emerging ones.

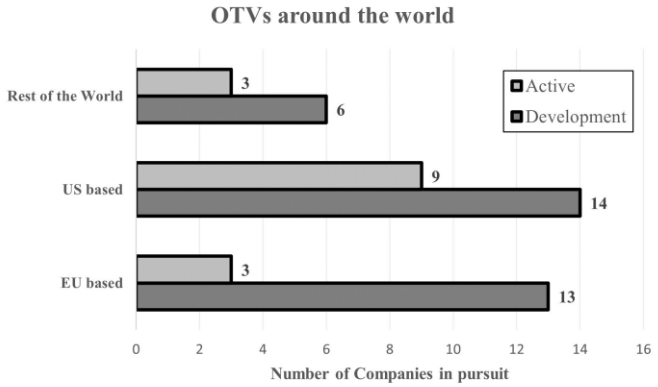


**Figure 2 - Number of companies in the field of OTVs. Numerous companies have multiple active projects considered only once**

The increase in space technology users, particularly driven by the steep increment in utilization by historical users, is expected to drive the demand for many of these new systems in the market. The trend toward miniaturization of technologies is a key driver for these developments. As the number of small satellites in Low Earth Orbit (LEO) continues to grow, accommodating heavy and voluminous propulsion systems becomes challenging. Consequently, there is an increasing demand for last-mile delivery services in space, capable of facilitating the hard task of reaching the final orbit destination for the customers.

The proliferation of small satellites with limited on-board propulsion, which depend on external devices to reach their destinations, is already evident in LEO. While the replacement of small spacecraft and CubeSats in LEO is relatively swift, reaching more distant orbits such as Medium Earth Orbit (MEO), Geostationary Orbit (GEO), Lagrangian points, or Lunar orbits presents more challenges. Satellites destined for these orbits are typically larger and more complex, and they often operate independently due to the difficulties associated with reaching these destinations.

Users of these satellites typically seek long operational lifespans spanning several years. To achieve both the required positioning maneuvers and a decade of operation, the common solution is employing highly efficient electric propulsion systems. These systems enable optimal utilization of on-board propellants and facilitate prolonged mission durations. The integration of OTVs in these orbits could significantly influence the sector in several ways. It could alleviate the delivery burden from the spacecraft, enabling customers to carry more propellant on board. Additionally, it could actively service spacecraft by refueling or conducting direct maintenance, prolonging their lifespan. OTVs hold the promise of providing a diverse range of services beyond last-mile delivery. These services include on-orbit repairs and maintenance to active debris removal, spacecraft refueling, orbiting tanks, on-orbit manufacturing, sample return, astronauts support and other in-situ operations.

From the customer's perspective, the choice of utilizing OTV services depends on various mission-specific factors. However, the appeal of OTVs that offer diverse services is evident, and companies can develop a compelling business case around these capabilities. Designing a versatile and modifiable orbital stage capable of handling complex missions poses several challenges, with careful consideration required for the characteristics of the propulsion system. These systems often take on the responsibility of propulsion requirements from other devices, leading to multiple options and trade-offs, including the selection of suitable propellants and technologies [2].

The process of choosing the most appropriate design options involves meticulous consideration of both customer requirements and internal factors such as cost, complexity, and ground and on-orbit operations. The study specifically examines the use of chemical propulsion systems due to their capability for short transfer times and orbital operations, which can be a significant factor in meeting customer needs. To ensure an affordable service, the ideal system should be easily manageable during both orbital and ground operations, and adaptable to a wide range of mission requirements, maintaining versatility.

The aspect of ground operations is often overlooked and taken for granted. Ground operations can significantly increase the overall cost and complexity of a mission, and any OTV provider should aim to minimize their impact as much as possible. The use of propellants that do not require complex handling during ground operations, for instance, could improve the situation. In addition, self-pressurizing propellants promise to offer both a simplification of ground operations, reduced cost of propellants and simplification of the overall system. The chemical compounds are reviewed in the following section, and the main feature and strength of these propellants lie in their inherent feeding pressure. The simplification of a spacecraft, reducing the number of components, is a crucial feature that offers good prospects for increasing the overall reliability of the system. For long-term and high-cost missions, this feature could be more valuable than a limited difference in performance. The complete elimination of the pressurization subsystem would avoid the use of pressure regulators and valves, components renowned to be highly susceptible to failure.
During the preliminary design of OTVs possibly based on these self-pressurizing compounds it is crucial to thoroughly study whether the new propellants are compatible with mission requirements. Apogee engines, depending on the mission, often fire for prolonged durations, up to 100 minutes [4,5]. An external pressurization system is capable of controlling and stabilizing the system to accommodate such extended firings. The feasibility of self-pressurizing compounds enduring such requirements needs careful examination, including whether additional design support may be necessary.

## IV. Propellants Comparison and Perspectives against the reference scenario

The present study focuses on compounds that can be considered "*green*" and that exhibit a high vapor pressure at nominal operating temperatures, that for in-space conditions are fixed in a range between 273 K (0°C) and 288 K (15°C). The former definition is linked to the human compatibility with the propellants, while the latter is connected to the inherent properties of the chemical compounds researched for the propulsion system.
For more than sixty years, the use of hydrazine-based compounds and nitrogen tetroxide has dominated the space propulsion industry due to some chemical properties that make them highly performing in terms of thrust parameters, storage, and the relatively simple design of the propulsion system. Specifically, unlike many fuels, hydrazine-based propellants are hypergolic when coupled with nitrous tetroxide, meaning that ignition occurs without any other energy source, simply as a result of the mixing process. In addition, hydrazines can be stored as a liquid at ambient temperature, with reduced need for temperature or pressure control systems as in the case of cryogenic propellants. Unfortunately, among the major drawbacks associated with the use of such propellants there is their toxicity and corrosive effects, along with their carcinogenic nature, increasing the risk of ground operations and requiring a significant effort for safe handling. Both derivatives of hydrazine (Unsymmetrical dimethylhydrazine - UDMH and Monomethyl hydrazine - MMH) are considered dangerous chemical compounds, posing life-threatening risks upon long-term or repeated exposures, and Nitrogen Tetroxide (NTO) is a well-known toxic compound, fatal through inhalation or contact. There are many reasons to opt for safer propellants, mainly connected to institutional boundaries, cost-related opportunities, summarized in Table 1.

| Source of Constraint | Type of constraint | Requirement on propulsion system |
|---|---|---|
| Institutional | - EU and international regulations<br>- Management and handling of hydrazine<br>- Re-entry of parts | - Non-Toxic<br>- Easily manageable<br>- Low risk |
| Cost-Related | - Long and complex ground operations<br>- Trained and expensive personnel<br>- Management of compounds | - Available compounds<br>- Reduced hazard during handling |
| Reference scenario | - Liquid-storable propellants (non-cryogenic)<br>- High vapor pressure at reference temperature | - Liquid or gaseous at ambient conditions<br>- Non-cryogenic |

**Table 1 - Constraints to selection of propellants**

In Europe, the European Chemicals Agency (ECHA) proposed the identification of hydrazine as a Substance of Very High Concern (SVHC) due to its carcinogenic properties, and it is foreseen a possible ban or forced reduced use in the coming years. This event would strongly impact the space sector, hence the research on alternatives is a growing field [6–11]. Other countries appropriately acknowledge the dangers associated with the handling of toxic propellants, and numerous regulations are in place to mitigate these risks. These regulations aim to minimize the hazards related to the management and handling of these compounds. Some measures include the complete evacuation of the room

during loading operations in ground operations and the use of Self-Contained Atmospheric Protection Ensemble (SCAPE) suits. The multitude of regulations leads to extensive, prolonged, and often costly operations, which could be significantly simplified by using alternative propellants. In view of streamlining the spacecraft preparations, possibly having a system ready to launch in a reduced timespan, the research of greener alternatives is more diffused, especially for OTV applications.

In this work, and in the overall space propulsion research around the world, the downsides described above are treated as a springboard for the development of newer, more *green* alternatives. The term *green* lacks a strict definition and often includes environmental aspects, such as the lifecycle assessment of propellants and their impact on the overall ecosystem. Emissions, in this case, are not a primary concern, as the focus is on in-space propulsion. In the space it is considered *green* any substance that is not extremely toxic and that can be managed with relatively simple operations and without needing dedicated expensive procedures and trained personnel.

The definition of green propellants for spaceborne systems often excludes cryogenic compounds. Cryogenic components require storage at very low temperatures and high pressures, which is commonly incompatible with long term space systems. Although there are new developments that may enable the use of cryogenic compounds, such as liquid methane or liquid oxygen, for weeks-long missions in space using specific insulation methods, these systems are yet to be demonstrated, and their efficiency remains unverified. Chemical compounds that require a storage temperature below 253 K (-20°C) to remain liquid are not considered in the study.

Finally, this work focuses on compounds with a high vapor pressure at operating temperatures, a feature that further limits the pool of available propellants. In particular, since the only storable and green oxidizers are two, hydrogen peroxide and nitrous oxide, only the latter exhibits self-pressurizing features.

### A. Self-Pressurizing compounds and physical properties comparison

A self-pressurizing compound is a substance that, under operating conditions, can sustain a flow in the pipelines by its own vapor pressure, without requiring an external pressurization system. In the context of propellants, this means that the compounds are stored in a saturated liquid state, or compressed liquid and, due to cavitation or boiling change of phase, produce a vapor phase that creates and sustains internal pressure.

Nitrous oxide ($N_2O$) is an example of a self-pressurizing compound at operating temperatures. Despite being an ordinary compound available for civilian use and utilized in multiple fields of application, it is also commonly utilized as oxidizer for hybrid engines and chemical thrusters. It is doubtlessly the widest available self-pressurizing compound, and the only conventional oxidizer presenting this property. It is, hence, utilized as reference oxidizer. The other compounds included in the study, most of them under the definition of light hydrocarbons, are analyzed as fuels coupled with Nitrous Oxide as oxidizer. The propellants are initially compared in terms of physical properties, especially vapor pressure, and then compared in terms of classical parameters for rocket propulsion performances, outlining the possible best choices and the motivations behind.

The investigated chemicals that respect the requirements listed in Table 1 of being compatible with humans, hence green, are storable at non-cryogenic temperatures as liquid and finally exhibit a relatively high vapor pressure (greater than 0.5 bar at 15°C) are listed in Table 2.

| **Fuels** | | **Oxidizer** |
|---|---|---|
| Acetylene | Pentane | Nitrous Oxide |
| Ethane | Propane | |
| Ethylene | Propylene | |
| Butane | Propyne | |
| Butene | Ammonia | |

**Table 2 - Considered Chemical Compounds as self-pressurizing propellants**

Most of the considered fuels are light hydrocarbons, excluding those that exist as supercritical fluids under ambient conditions. Ethylene has been included as a suitable candidate, being its critical point only slightly under the cutoff value of 288 K, it exhibits very high vapor pressure, making it attractive for self-pressurization.

The investigation of the propellants, summarized in Table 3, analyzed the storability of the various chemical compounds at the two temperature of 273 K and 288 K, commonly reachable during space operations. It is analyzed also the hazard associated with each compound, such as the risks of explosion and flammability as reported by international standard labels, summarized in Table 4.

| | Formula | Storability @ 0°C | | Storability @ 15°C | | | | |
|---|---|---|---|---|---|---|---|---|
| | | ρ [g/cc] | $p_{vap}[bar]$ | ρ [g/cc] | $p_{vap}[bar]$ | $T_{crit}$ [K] | $P_{crit}$ [bar] | Hazard |
| Ethane | $C_2H_6$ | 0.4007 | 23.78 | 0.358 | 33.64 | 305.3 | 48.72 | H220 |
| Propane | $C_3H_8$ | 0.5288 | 4.72 | 0.508 | 7.28 | 369.9 | 42.512 | H220 |
| Butane | $C_4H_{10}$ | 0.6009 | 1.026 | 0.584 | 1.75 | 425.1 | 37.96 | H220 |
| Pentane | $C_5H_{12}$ | 0.6457 | 0.243 | 0.631 | 0.46 | 469.7 | 33.67 | H224 |
| Ethylene | $C_2H_4$ | 0.342 | 40.85 | *Supercritical* | | 282.4 | 50.418 | H220 |
| Propylene | $C_3H_6$ | 0.5463 | 5.81 | 0.523 | 8.88 | 364.2 | 45.55 | H220 |
| Butene | $C_4H_8$ | 0.6185 | 1.28 | 0.601 | 2.16 | 419.3 | 40.05 | H220 |
| Propyne | $C_3H_8$ | 0.6521 | 2.64 | 0.623 | 4.30 | 402.4 | 56.26 | H220 |
| Benzene | $C_6H_6$ | *Freezing* | | 0.884 | 0.078 | 562.0 | 48.94 | H225 |
| Ammonia | $NH_3$ | 0.6388 | 4.27 | 0.618 | 7.25 | 405.6 | 113.63 | H221 |
| Toluene | $C_7H_8$ | 0.8855 | 0.009 | 0.872 | 0.022 | 591.8 | 41.26 | H225 |
| Acetylene | $C_2H_2$ | 0.7 | 26.9 | 0.69 | 39.17 | 308 | 61 | H220<br>H230 |
| RP-1 | $C_{10}H_{14}O_4$ | 0.81 | $\ll 0.1$ | 0.78 | ~0.1 | 676 | 22 | H226 |
| Dimethyl Ether | $C_2H_6O$ | 0.7 | 4.35 | 0.677 | 2.65 | 401 | 54 | H220 |
| Nitrous oxide | $N_2O$ | 0.9 | 31.1 | 0.82 | 44.88 | 309.5 | 72.45 | H270 |

**Table 3: Physical properties of the fuel candidates and initial selection in terms of associated hazard. Density refers to the liquid phase.[5]**

| Label | Hazard Statement |
|---|---|
| H220 | Extremely flammable gas |
| H221 | Flammable gas |
| H224 | Extremely flammable liquid and vapor |
| H225 | Highly flammable liquid and vapor |
| H230 | May react explosively even in the absence of air |
| H270 | May cause or intensify fire |
| H271 | May cause fire or explosion |

**Table 4: Physical hazard labelling.[6]**

Looking at Table 3, it is possible performing an initial assessment of the alternatives. Initially compounds that, although non-toxic, are too dangerous to handle are discarded. Compounds that present hazard labels of H230 have been discarded for their increased danger. For instance, acetylene, despite having a high value of vapor pressure at ambient temperature and hence being suitable for self-pressurization, has been discarded because of the high risks associated with its handling. Apart from being extremely flammable, it is a very unstable molecule, involving a great hazard of explosion when heated even in the absence of air.

The second selection has been performed discarding propellants that have an excessively low vapor pressure for the feeding system purposes, shown in Table 5. In fact, it is essential to examine whether the initial vapor pressure is high enough to propel the flow into the combustion chamber despite the present and unavoidable pressure losses along the feed line and through the injector. The combustion chamber pressure is not yet defined in this phase of the comparison, and the criterion adopted to declare the suitability is fixing a threshold. The criterion was selected to remain cautious regardless of the extracted phase from the tank and considering thrusters with relatively low combustion chamber pressure. Two temperatures have been considered, the conservative value of 15°C and the limit value of 0°C. With dedicated insulation, and possible heaters, different values could be reached, however the presence of such components is not assumed. To be considered suitable as self-pressurizing propellants, compounds need to have a vapor pressure greater than 8 bar at 15°C and 5 bar at 0°C. Compounds that are slightly lower than the threshold may

[5] Properties extracted from NIST website - https://webbook.nist.gov/chemistry
[6] Description from ECHA website - https://echa.europa.eu

still be considered suitable for self-pressurization since limited heating devices would be needed to raise the storage temperature to a suitable value. Furthermore, propellants within this range can be a viable option as long as slightly lower values of the chamber pressure than the threshold assigned in this study are allowed.

| Propellant | $p_{vap}[bar]$ @ 15°C | Self-pressurizing | $p_{vap}[bar]$ @ 0°C | Self-pressurizing |
|---|---|---|---|---|
| Ethane | 33.64 | Yes | 23.78 | Yes |
| Propane | 7.28 | Maybe | 4.72 | Maybe |
| Butane | 1.75 | No | 1.026 | No |
| Pentane | 0.46 | No | 0.243 | No |
| Ethylene | *Supercritical* | No | 40.85 | Yes |
| Propylene | 8.88 | Yes | 5.81 | Maybe |
| Butene | 2.16 | No | 1.28 | No |
| Propyne | 4.30 | No | 2.64 | No |
| Ethanol | 0.043 | No | 0.016 | No |
| Ammonia | 7.25 | Maybe | 4.27 | Maybe |
| RP-1 | 0.78 | No | < 0.1 | No |
| Nitrous Oxide | 44.8 | Yes | 31.1 | Yes |

**Table 5: Propellants analysis in terms of vapor pressure preliminary results.**[7]

Up to this point, the analysis results indicate that among the propellants meeting green requirements and proving to be more suitable for a self-pressurized system, only a little number of alternatives appear viable. Ethane and propylene are the most promising compounds, while ethylene could represent compelling options that would necessitate dedicated precautions. Propane and ammonia present interesting values that could be utilized with limited external supply in the form of heaters to raise the internal temperature and vapor pressure.

### B. Rocket Performance comparison

In the previous analysis, the chemical compounds have been investigated for their chemical features that could benefit the propulsion system without considering their applicability to rocket themselves. The propellants are here compared when applied to rocket propulsion. The only available self-pressurizing oxidizer is nitrous oxide, and all the various compounds analyzed have been investigated as fuel coupled with it.
To perform a comparative study, some of the engine parameters have been arbitrary set, such as the chamber pressure and the nozzle area ratio, set to respectively 4 bar and 100:1. These choices have the objective of determining the best propellant combination for the engine of an orbital stage, not to optimize the final selection. It is recognized that a combustion chamber pressure as low as 4 bar strongly impacts the performance of the engine and its final size and weight, however such a low value has been selected to include the greater number of propellants in the selection. In the study, all propellants have been analyzed, regardless of whether their low vapor pressure made them unfit in the previous phase. Combustion performance of the various combinations have been computed with NASA CEA, assigning a combustion pressure of 4 bar, 100:1 expansion area ratio, vacuum at the outlet, and the conservative feature of frozen flow at the throat. The parameters of interest are the ideal ratio oxidizer-to-fuel (ROF) and the correspondent specific impulse and combustion temperature.

| | Optimal ROF | max $I_{sp}$ $[s]$ | $T_c$ $[K]$ | $\rho_{eq}$ $[g/cc]$ @ max $I_{sp}$ |
|---|---|---|---|---|
| Ethane | 7 | 304 | 3095 | 636.4 |
| Propane | 6.5 | 303 | 3104 | 696.8 |
| Butane | 6.5 | 295 | 3109 | 715.8 |
| Pentane | 6 | 294 | 3112 | 723.9 |
| Ethylene | 5.5 | 307 | 3194 | 630.3 |
| Propylene | 6 | 304 | 3168 | 697.6 |
| Butene | 7.5 | 270 | 2798 | 721.8 |

[7] Properties extracted from NIST website - https://webbook.nist.gov/chemistry

| | | | | |
|---|---|---|---|---|
| Propyne | 5 | 308 | 3287 | 718.4 |
| Ethanol | 4 | 299 | 3018 | 752.2 |
| Ammonia | 3 | 307 | 2883 | 703.2 |
| RP-1 | 6.5 | 300 | 3120 | 751.3 |

**Table 6: Fuel rocket performance with $N_2O$ as oxidizer. Output from NASA CEA iterations [12].[8]**

It is evident that the combustion temperatures are consistently high. Managing such temperatures poses significant challenges, even with state-of-the-art materials. However, recent manufacturing advancements, including additive manufacturing, have rendered complex geometries such as regenerative cooling more affordable and feasible. The presence of regenerative cooling, however, would impose a further pressure loss in the pipelines, and it must be considered if the self-pressurizing propellants can withstand it [13]. While the challenge of high combustion chamber temperatures is acknowledged, it is not thoroughly analyzed in the assessment of propellant suitability.

To assess the performance of propellant combinations, the specific impulse is commonly employed, providing a useful measure of the efficiency of various compounds as rocket propellants. The analysis reveals that ethylene, propyne, ammonia, propylene and ethane are the propellants with the highest values, that are comparable with values of common toxic propellants (315 s at equivalent conditions). The differences in specific impulse between all the alternatives are relatively negligible, and all the propellants exhibit high performance.

Unfortunately, most of the analyzed compounds exhibit relatively low density. The average, or bulk, density of a bipropellant is contingent on the density of both propellants, but also the chosen oxidizer to fuel ratio, as expressed in Eq. 1. The reference ambient temperature and liquid storage phase are utilized to calculate each compound density.

$$\rho_{eq} = \frac{\rho_{fu}\rho_{ox}(1+ROF)}{\rho_{ox}+\rho_{fu}\cdot\ ROF} \qquad \text{Eq. 1}$$

The density of the mixture is an important criterion to consider. As a matter of fact, low densities correspond to higher tankage fractions at equivalence of propellant mass, because the propellants require larger storage volumes. To account for both the overall performance and the density, it is defined the volumetric specific impulse as the product between the density and specific impulse. This parameter is plotted against the combustion temperature in Figure 3, showing that, as mentioned, the combustion temperature is consistently high, and that there is little distinction between denser and less dense propellants in terms of temperature.

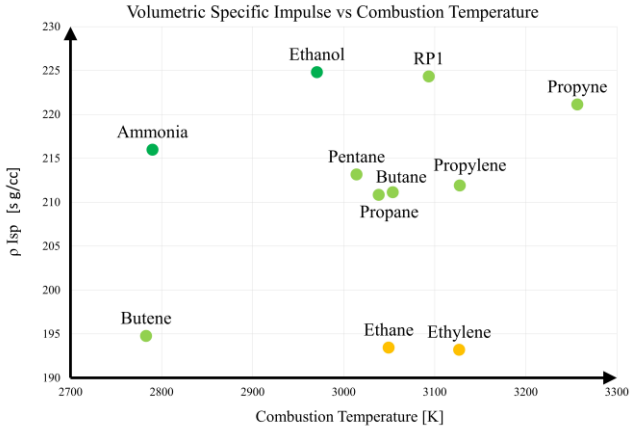


**Figure 3 - Combustion Temperature and volumetric specific impulse. Dot colors describe density, greener meaning more dense and yellow/red low density.**

Finally, Figure 4 shows the specific impulse depending on the bulk density. The bulk density strongly depends on the oxidizer to fuel ratio chosen for defined engines. This parameter is influenced by various factors and significantly impacts engine performance, including its combustion temperature. Optimizing the ROF for a defined engine requires consideration that must include overall mass requirements. For instance, ethane exhibits good performance in terms of specific impulse, but relatively low bulk density compared to other alternatives when the ROF is fixed for maximum performance. Utilizing ethane in an oxidizer-rich configuration, instead, could achieve overall densities comparable

[8] https://cearun.grc.nasa.gov/

to other alternatives, or at least enhance its situation, at the cost of a decline in specific impulse. It should be noted that ethane has also a less steep decline in specific impulse than other mixtures when the ROF is not at its ideal maximum point.

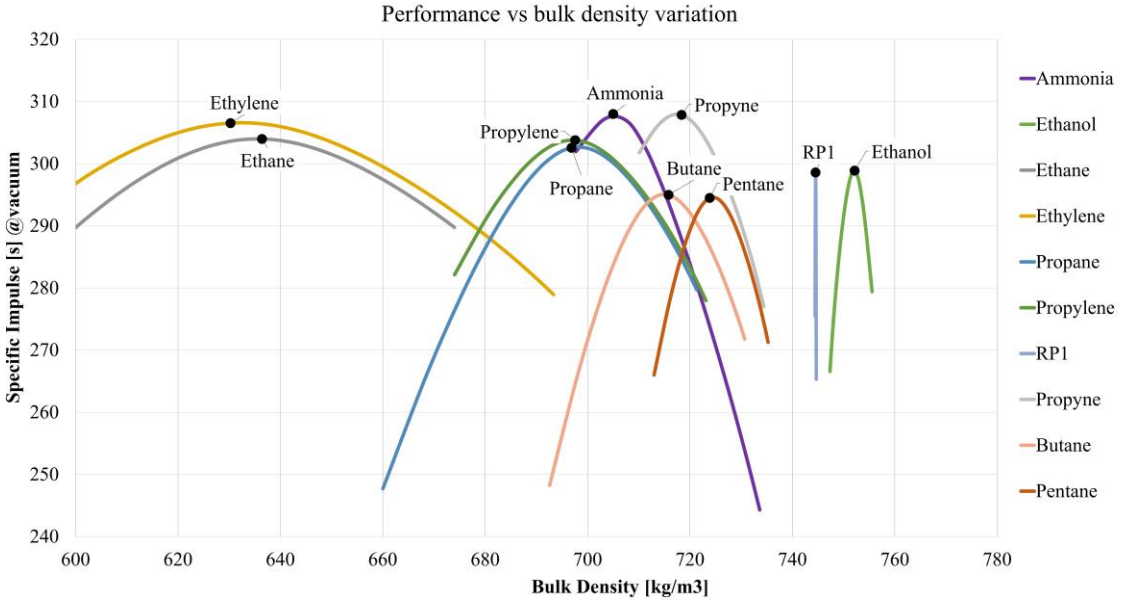


**Figure 4 - Specific Impulse varying the oxidizer to fuel ratio and consequently the equivalent bulk density.**

The comparison also includes propellants with low vapor pressure at ambient temperature, such as RP-1 or ethanol. These propellants are frequently employed in the space sector as fuels, and their inclusion is associated with the suggested feasibility of utilizing the oxidizer, nitrous oxide, to pressurize itself and the fuel. The safety of this proposed architecture is not addressed and requires considerations regarding the potential risks associated with storing oxidizer and fuel in close proximity. However, such a configuration could lead to mass and volume savings in terms of tanks, and these propellants have higher density compared to other light hydrocarbons considered in the study, while maintaining comparable specific impulse and combustion temperature.

### C. Conclusions - Promising compounds

The selection analyzed a multitude of various chemical compound alternatives. Most of the self-pressurizing and volatile compounds normally present on Earth are highly toxic or dangerous for human health and hence have been discarded prior the inclusion in the selection process. There is only one self-pressurizing oxidizer, nitrous oxide, that hence has been used as reference during the comparison.

From the physical characteristics, it is clear how most of the alternatives are light hydrocarbons. Of these, only a few are stable enough and possess a high vapor pressure compatible with the strict requirements imposed by the space sector and mission scenario. In particular, only ethane and propylene appear as viable choices coupled with nitrous oxide, while propane and ammonia could be possible options with accurate design and dedicated solutions. Between ethane and propylene, the former presents higher self-pressurizing properties and would allow greater design freedom. When looking at density, all propellants possess a quite low density even if stored as liquid. The performances are relatively high for all the propellants, with little difference between them, as well as the connected combustion temperature. The high combustion temperature implies that dedicated design choices such as regenerative cooling must be considered. The main drawback of the solution is that it imposes a pressure loss to a system that does not possess high feeding pressure.

In summary, ethane or propylene appear as the most convenient. It must be noted that various private entities around the world have already developed solutions based on self-pressurizing compounds, with the same conclusions of this selection. As a matter of fact, as shown in Table 7, the utilized solutions revolve around the two choices highlighted in the selection.

| Company | Selected Solution | Location | Source |
|---|---|---|---|
| Dawn Aerospace | Propylene – Nitrous Oxide | EU-NZ | Website[9] |
| Impulse Space | Ethane – Nitrous Oxide | US | Website[10] |
| VAST - Launcher | Ethane – Nitrous Oxide | US | Website[11] |
| D-Orbit | Light Hydrocarbon – Nitrous Oxide | EU | Website[12] |
| Gate Space | Ethane – Nitrous Oxide | EU | Website[13] |
| ISPTech | Ethane – Nitrous Oxide | EU | Website[14] |

**Table 7 - Industrial providers of thruster solutions based on self-pressurized propellants**

Other compounds such as ammonia and propane could be viable options with dedicated troubleshooting. Although ammonia is toxic and dangerous, it is also one of the most produced chemicals in the world. It is estimated that its production will grow, and it is deemed as the future energy carrier. As a matter of fact, it has a higher density of hydrogen atoms than liquid hydrogen, but with extremely reduced troubles in storage and management of the compound. Moreover, there are various studies of the presence of ammonia in solar system bodies.

## V. Challenges associated with Self-Pressurizing Propellants

The study concludes by introducing the predicted challenges to overcome for future detailed designs of systems based on self-pressurizing propellants. The physical characteristics of the compounds and the evolution of the pressure inside the tanks is crucial to design the very delicate propellant management subsystem. Numerous distinct models are present in the existing literature that describe the self-pressurization behavior inside contained tanks during mass ejection. However, the models have very seldomly been applied to a wide range of compounds and have been validated using a single compound, typically nitrous oxide or carbon dioxide.

The analysis does not dive into detailed description of the different models and their relative accuracy, instead it summarizes the main features of each promising model and the connected issues that need to be solved in order to be applied to a broad range of systems. Space thrusters, depending on their size, often have very stringent requirements. It is common, for apogee engines, to fire in continuous mode for a prolonged period (i.e. up to dozens of minutes), to be reignited after a long coasting phase of days, and to be excellent in heat management. When addressing these requirements, the propellant management system and its performances are crucial features to consider, and the models that describe the involved physics phenomena are key elements to create a robust design.

Generically, the models need to address two interconnected but still independent phenomena:

- Self-Pressurization and change of phase mechanisms inside the tank.
- Mass Flow Rate of Saturated Fluids.

These phenomena are crucial for the effectiveness of a self-pressurizing system, especially in the case of only one propellant with self-pressurization characteristics.

### A. Tank Emptying Models

In a propulsion system, monitoring the evolution of tank-related parameters is crucial. Traditional propulsion systems are relatively straightforward to simulate, as the involved phenomena are well-known and relatively simple. In contrast, self-pressurizing compounds present several challenges during the modeling phase. The presence of draining saturated fluids introduces a series of complex physical phenomena that are difficult to predict, including cavitation, bubble creation, growth, and detachment from the wall, condensation, and various heat exchanges. All these phenomena are challenging to predict and extremely difficult to model [14]. Typically, each one is modeled separately,

[9] https://www.dawnaerospace.com/
[10] https://twitter.com/GoToImpulse
[11] https://twitter.com/launcher
[12]https://www.esa.int/Enabling_Support/Space_Transportation/Boost/ESA_gives_a_Boost!_to_D-Orbit_industrial_ramp-up_plans
[13] https://gate.space/
[14] https://www.isptech.space/

often focusing on small scales, such as the bubble growth problem. However, modeling the tank emptying requires capturing the big picture, considering the complex interplay of various phenomena on a larger scale [15].
The accuracy of the analysis is significantly affected by the selection of the sub-models and their assumptions. Different authors developed various models with the aim of capturing the dynamics of self-pressurized and saturated fluids within a tank under discharge conditions. The most relevant models are the Equilibrium Model (0D), Casalino & Pastrone (0D), Ziliac & Karabeyoglu (0D) [16], Zimmerman (0D/1D hybrid model) [17,18], Foletti-Magni-La Luna (0D) [19], and Borgdorff (0D). Most of the models have various strengths but rely on various levels to some sort of correction parameters that make them difficult for a wider application. It follows a brief description of three of the most prominent models.

1. *Homogeneous Equilibrium Model (HEM)*

Among the models listed above and present in the literature, the homogeneous equilibrium model stands out as the simplest but still effective model, capable of predicting the pressure behavior with satisfactory accuracy but unable to capture transient dynamic. Specifically, the model performs well in the steady-state discharge region but performs poorly elsewhere. The main assumption of the model considers vapor and liquid as two phases in thermodynamic equilibrium throughout the whole emptying process. As a result of this simplification, the bubbles formation and growth time is neglected, and the change of phase occurs instantaneously when the tank valve opens.
The model is relatively simple to implement, and the results can be considered accurate for preliminary evaluation of the operations. It is applicable regardless of the phase that is being extracted.

2. *Zilliac & Karabeyoglu Model (ZK)*

Zilliac and Karabeyoglu presented a non-homogeneous, non-equilibrium model, consisting of two non-saturated control volumes, one for the bulk liquid and one for the ullage gas which is divided by a thin layer of saturated liquid (intermediate surface). Each node has two governing equations. To capture boiling and condensation effects between the two nodes, a heat transfer sub-model was necessary in this model. In particular, the heat transfer between the liquid and the intermediate surface, and the heat transfer between the intermediate surface and the vapor are computed using correlations for natural convection. The model is partially able to capture transient behavior of the tank draining but relies on an empirical coefficient $E$ to correct the actual heat transfer that the model underestimates.
The model adds a discreate amount of complexity, but nonetheless results are still a strong approximation of real data. The need for correction factors is a disadvantage since such parameters are difficult to estimate.

3. *Zimmerman Model (ZM)*

Zimmerman's model directly builds on the ZK model, but it introduces a higher degree of complexity. It incorporates an additional degree of freedom to represent bubbles within the liquid. The model still consists in three volumes of control representing the liquid and gaseous phase and the interface. In the model, the liquid phase is further discretized in the vertical direction, and a set of partial differential conservation equations is included for the bubbles growth and evolution. This addition of degrees of freedom categorizes Zimmerman's model as a hybrid 0-D/1-D, and allows it to reach higher levels of accuracy at the expense of an evident increased complexity. Unfortunately, the model still relies on semi-empirical parameters to estimate the number of bubbles created during the change of phase due to cavitation.

4. *Folletti-Magni-La Luna Model (FML)*

The model presents a similar structure to the ZK model. It consists of two non-saturated control volumes, one for the ullage gas and one for the bulk liquid. It includes a saturated liquid layer positioned between these non-saturated nodes to allow easier modeling of the exchange of mass and energy through the different phases. The model considers the tank as an open control volume, and it accounts for the mass and energy exchange between the phases in the form of evaporation and condensation. The heat transfer between the tank and the surrounding environment is neglected. The governing equations consider the mass and energy conservation specified for the ullage and the bulk liquid. The main difference with respect to ZK is the presence of a boiling threshold that accounts for the onset of bubbles in the liquid phase inside the tank. Due to this factor, the model is able to better account for the boiling without the difficulties associated with bubble modeling. The model has a level of complexity equivalent to the ZK model, but it is better able to capture the transients. The model only lightly relies on correction parameters to estimate bubbles growth and detachment. Although the model does not directly include the modelling of bubbles, their number is still a semi-empirical parameter.

### B. Saturated fluid mass flow rate sub-models

The development of an overall model describing the evolution of the various design parameters of the propulsion system is crucial, and phenomena connected to saturated fluids are more complex than normal fluids. The mass flow rate of saturated fluids presents the typical challenges of a biphasic flow and necessitates various approximations.

Depending on the specific phase that is decided to drain from the tank, different and dedicated mass flow rate models have to be accurately selected and tuned. These models couple with the emptying models and describe the evolution of fundamental parameters for the correct operations of the entire system. Literature provides many modelling options, at various levels of complexity. The most common models are described hereafter, with the first two describing the classical behavior of single-phase flows, and the latter introducing the complexities of bi-phase flows.

1. *Liquid Single Phase Incompressible (SPI)*

This model is the most common description of liquid flow, deriving from Bernoulli. It fits properly with a multitude of compounds and models the fluids as single-phase incompressible, inviscid, and irrotational flow with no body forces acting on it.

$$\dot{m}_{SPI} = C_D A \sqrt{\frac{2\,\rho(p_1 - p_2)}{1 - \frac{A_2}{A_1}}} \qquad \text{Eq. 2}$$

2. *Single Phase Compressible (SPC)*

The model is utilized for propulsion systems involving vapor injection, predicting the behavior of a flow in full gaseous phase. The mass flow rate through an orifice is an isentropic process, and the vapor is treated as a real gas, *n* is the isentropic exponent for real gas.

$$\dot{m} = C_D A \sqrt{2\rho_1 p_1 \frac{n}{n-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{n}} - \left(\frac{p_2}{p_1}\right)^{\frac{n+1}{n}}\right]} \qquad \text{Eq. 3}$$

When the flow is choked, and then independent of downstream pressure fluctuations, the maximum flow rate through the injector is provided by Eq. 4. where is included the compressibility factor *z* appearing in the mechanical equation of state for real gas [20].

$$\dot{m}_{SPC} = \frac{pAn}{\sqrt{nzRT}}\sqrt{\left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}} \qquad \text{Eq. 4}$$

3. *Two-phase mass flow rate models: HEM and Dyer.* [21]

The mass flow rate models of saturated flows are more complex because must consider change of phase or dispersed phase. Applications involving self-pressurizing feed systems operate at pressure in the pipelines close to the compound saturation values. The local pressure of the flow accelerating through the injector dictates the phase of the flow itself and in case of liquid can drop below the vapor pressure, causing the occurrence of cavitation, or in the case of vapor could slow down, causing condensation.
There are multiple models in literature describing the behavior of compounds, here are mentioned the two prevalent: the homogeneous equilibrium model (HEM) and the Dyer model. HEM is the simplest of all the two-phase models, where the flow through the injector is assumed to be isentropic with the two phases in thermodynamic equilibrium and zero slip velocity.

$$\dot{m}_{HEM} = \rho_2 A\sqrt{2(h_1 - h_2)} \qquad \text{Eq. 5}$$

Unfortunately, the model is unable to predict choking conditions linked to cavitation and after reaching the critical value, the mass flow rate keeps decreasing instead of remaining constant. The second model, also utilized in this study, is the one proposed by Dyer. This model takes into consideration non-homogeneous flow, indicating the absence of a zero-slip velocity between the two phases. Additionally, it accounts for non-equilibrium effects arising from the finite bubble growth speed and the superheating of the liquid phase during expansion.

$$\dot{m}_{Dyer} = A\left(\frac{k}{k+1}\dot{m}_{SPI} + \frac{1}{k+1}\dot{m}_{HEM}\right) \qquad \text{Eq. 6}$$

The complexity of the model is positioned between the Single-Phase Incompressible model (SPI) and the Homogeneous Equilibrium Model (HEM) through the Dyer constant $k$, which is proportional to the ratio between the bubble growth time and the fluid residence time. The Dyer constant is affected by the pressure drop across the injector

as well as the vapor pressure of the fluid upstream. It is noteworthy to point out that in the case of saturated liquid extraction when $k = 1$, the weight of the two contributions is the same, and the mass flow rate provided by Dyer is just the arithmetic average between the SPI and the HEM. In such a case, the Dyer model loses accuracy in describing the flow as the value of $k$ remains constant regardless of the upstream variations.

### C. Preliminary results applying simplified models

Among the models previously discussed, the Homogeneous Equilibrium Model for tank emptying has been applied to a configuration involving two tanks filled with oxidizer and fuel respectively to study and investigate the evolution of the various engine parameters. The selected propellants used for the investigation are ethane and nitrous oxide for their high and similar vapor pressure and overall promising properties.

Separate numerical analyses have been conducted for both liquid and vapor extraction to evaluate the constraints and benefits associated with each case in terms of delivered performance. The choked SPC model has been used to characterize the mass flow rate of the injected vapor, while the Dyer model was used to describe the injection of saturated liquid accounting for the resulting cavitating flow. In this context, it is crucial to note that during the emptying process, the pressure and temperature within the tanks decrease, with an impact on the extracted mass flow rate and on the oxidizer to fuel ratio of the engine. Due to these variations, specific impulse and thrust may vary from their nominal value throughout the burning time, experiencing a decrease that has been evaluated. The models are still an approximation of the real behavior of the engine, that should be investigated in relevant environment because these phenomena pose a challenge to the delivered performance and may be the source of constraints on maximum burning time. When the tank pressure reaches a certain lower threshold value during discharge, the self-pressurization is no longer able to feed the propellants into the chamber, posing a great limitation to the selection of combustion chamber pressure and a further constraint to the maximum burning time.

In the study, it has been performed a parametric analysis of a 1 kN engine at nominal conditions, and the evolution of pressure, thrust and oxidizer to fuel ratio has been investigated. It has been analyzed the comparison between liquid and gaseous draining phases. The nominal and initial mass flow rate for both phases is equivalent, being set by the imposed thrust level, as well as the specific impulse, fixed at the maximum value with its corresponding ROF. However, the pressure drop in the tank and the evolution of the mass flow rate during the firing strongly depend on the phase extracted.

When considering the overall system, it is impossible to decouple the tank emptying model from the mass flow rate. Figure 5 on the left-hand side shows the ideal case of a fixed and constant mass flow rate over time, set at the nominal value to obtain the required thrust level. The vapor phase extraction causes a greater pressure drop than the liquid draining over the same time span because the gas has a lower density than the liquid, resulting in a greater volume of extracted mass. Unfortunately, the constant mass flow rate can be obtained only by a complete decoupling of the tank emptying and mass flow rate models, which is impossible unless dedicated mechanisms are in place.

During the tank emptying, the mass flow rate strongly decreases, causing the pressure drop trend shown in Figure 5, right-hand side. The pressure drop in the tank is still smaller for the liquid than for vapor draining, but for both phases the drop is smaller than what is expected in the ideal case with constant mass flow rate, and the motivation lies in the strong variation of mass flow rate over time, that in the ideal case was not present.

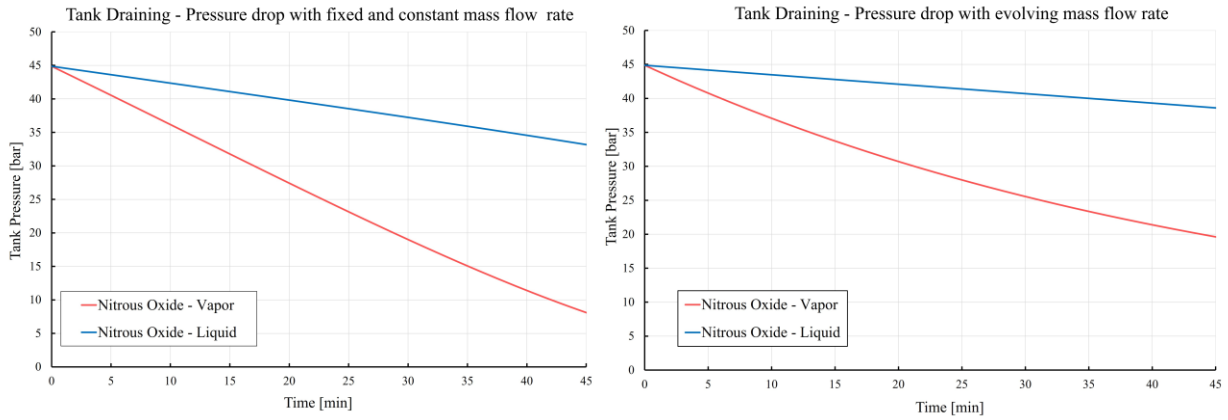


**Figure 5 - Pressure evolution inside the tank with different phase extraction, predictions using the HEM model for the tank emptying, left hand-side picture constant nominal mass flow rate and right-hand side coupled with the SPI for liquid extraction and Dyer for vapor extraction.**

The mass flow rate model, as a matter of fact, is directly and strongly coupled with the tank emptying model, because itself depends on the upstream conditions. The evolution of the mass flow rates is naturally related to the phase extracted and to the effects that the extraction causes on the tank conditions, especially the pressure. The difference between liquid and gaseous mass flow rate during the same time span is high, as shown in Figure 6, using the starting values of mass flow rate from the reference 1 kN engine.

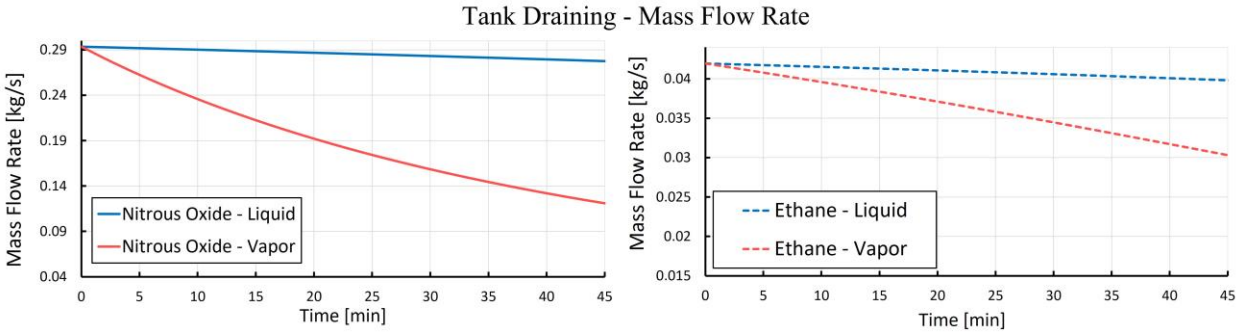


**Figure 6 - Mass Flow Rate evolution in the cases of liquid or gaseous phase extraction for both propellants. Predictions using the HEM model for the tank emptying coupled with the SPI for liquid extraction and Dyer for vapor extraction.**

The reduction in mass flow rate has strong implications for tank draining. A reduced mass flow rate compared to the nominal point leads to a decrease also in pressure drop in the tank, that is beneficial on the maximum allowed burning time. Although the liquid mass flow rate experiences a minimal decrease within a 45-minute time span, it still results in a 5-bar difference in the tank compared to the ideal constant case. Despite a significant reduction in vapor extraction mass flow rate over time, the draining still induces a greater pressure drop in the tank compared to liquid.

The overall behavior of the system mirrors on the engine performance and adversely impacts the thrust delivered over the burning time, as well as the specific impulse, as shown in Figure 7. The figure shows all the various phase combinations, and it is clear that the primary influence on thrust and specific impulse is linked to the selection of the nitrous oxide extraction phase. The motivation lies in the fact that the mass flow rate of nitrous oxide remains an order of magnitude higher than that of ethane, regardless of the extracted phase of it. Consequently, the thrust profile is less affected by the decrease of ethane mass flow rate, regardless of its phase.

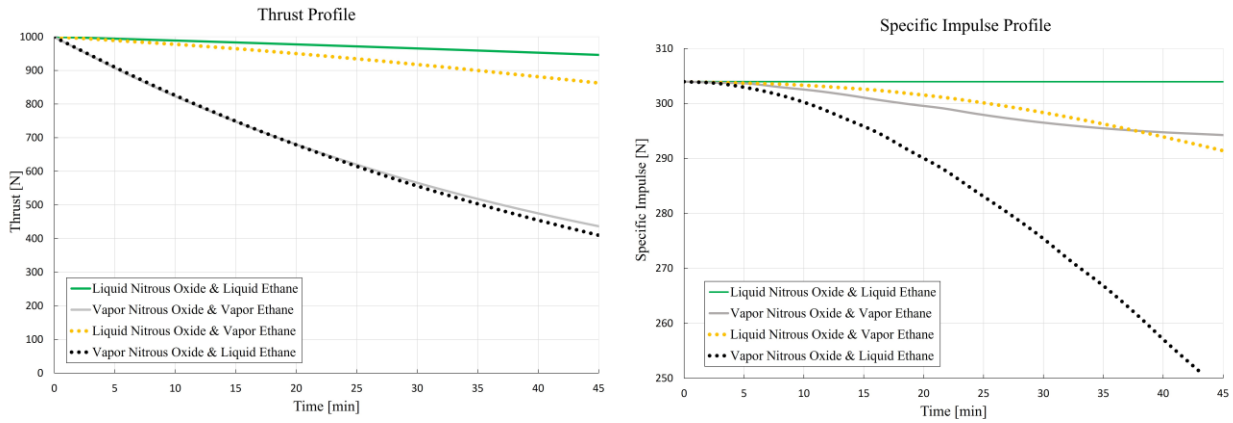


**Figure 7 - Thrust and Specific Impulse profiles defined by the evolution of mass flow rates during burning time**

The main conclusion out of Figure 7 is that the smallest loss in performance over burning time in terms of thrust is obtained by extracting the oxidizer in liquid phase, regardless of the ethane phase.
In terms of specific impulse, values exhibit a significant decline over relatively short time span. The extraction of the vapor phase leads to shifts in oxidizer-to-fuel ratio values that are challenging to control, especially when fuel and oxidizer are extracted in different phases. The most stable performance occurs when both propellants are extracted either as liquid or as vapor, although the latter case results in a reduced specific impulse over time. The worst-case scenario occurs when vapor nitrous oxide and liquid ethane are extracted, as the mass flow rate of the oxidizer decreases more rapidly than that of the fuel. This results in a fuel-rich mixture, leading to decreased efficiency.

### D. Models next steps

Numerous and intricate physical phenomena occur in the propulsion system, feeding lines, and tanks. The literature abounds with diverse models attempting to encapsulate the critical phases without introducing overly complex setups that would be challenging to implement. Various attempts have been made to enhance the models' resolution, but they often rely heavily on tuning and correction parameters that are difficult to generalize. Although not flawless, simpler models like the HEM for tank emptying can effectively capture the overall behavior of parameters within the tank during the discharge of saturated fluids. For the study, these relatively simple models have been implemented to study the overall behavior of a reference propulsion system. While the employed models are simplified, they are sufficient to capture the evolution of the parameters of interest, but there is a need for improvements to account for various design parameters, such as tank shape and volume, as well as heat exchange with external heat sinks or sources.
The analyses highlight the significance of the draining phase for ensuring the stability of engine performance. For a more consistent thrust over time, the optimal solution involves draining liquid nitrous oxide. Specifically, draining liquid oxidizer results in an acceptable 10% reduction in thrust occurring only after more than 40 minutes of continuous firing in both cases of gaseous or liquid ethane extraction. Conversely, in the case of gaseous phase draining of the oxidizer, the thrust decrease is more pronounced. In this scenario, a 10% reduction in thrust occurs in less than 5 minutes of continuous firing, indicating that this draining strategy may not be compatible with prolonged maneuvers.
It should be noted that the chosen phase for extraction significantly impacts the ease and complexity of mass flow rate control. Extracting gas is more straightforward to control, as a choking orifice would be sufficient to regulate it, effectively decoupling upstream and downstream phenomena. In the design phase, accurately predicting the maximum duration of the burning time is crucial to minimize thrust loss during the burning period. Given that typical apogee maneuvers could last up to 100 minutes, careful consideration of thrust levels is essential in the analysis.

### E. Spacecraft operations challenges

Self-pressurization represents a pivotal technology in the small satellite space panorama. Indeed, it can lead to significant cost and volume savings, allowing the feeding system to be freed from either an extra pressuring tank or turbopumps. Furthermore, in a self-pressurization system, the pressure inside the vessel could be modulated theoretically with no upper limit by controlling the temperature inside the vessel, as these two physical quantities

strongly depend on each other. The latter option is not investigated in detail in this study, but it may support the solution of the described challenges, even though it introduces further claims.
From a spacecraft system point of view, the challenges connected to the utilization of self-pressurizing propellants can be summarized as:

- Temperature control and power budget;
- Propellants gauging;
- Satellite Center of Gravity (CoG) estimation;
- Two-phase injection control.

Temperature control is the aspect that most closely relates to the propulsion system's performance. This control could be achieved by an internal or external active control system. Generally, the external regulation is preferred, and it can be achieved by means of heaters installed on the external tank surface, since the internal installation would lead to additional complexity related to material compatibility and local propellant overheating. The real challenge is the fact that this configuration leads to both profound uncertainties in temperature values inside the vessel and delays in system responses, that would necessitate of a long period of heating before reaching conditions adapt to firing. The latter is a direct consequence of a non-instantaneous temperature balance, as the rate of heat exchange is limited in real applications, yielding maneuverability issues during dangerous situations (e.g., Collision Avoidance Maneuver). Power budget is strictly related to the previous point since larger tanks can cause high power consumption due to the low-efficient heating system mounted on the tanks, usually composed of electrical resistances.
The remaining issues listed above can be treated together since they affected the reliability and attitude control of the overall satellite. The propellant estimation is a challenge due to the self-pressuring technology itself, as the vapor pressure pressurizes the liquid phase of the propellant, but it doesn't allow for prediction of the amount of liquid and/or vapor inside the pressure vessel. Indeed, the dispersion of phases and the complexity of modeling and predicting tank dynamics make the incorporation of sensors challenging.

The latter issue is connected also with the third and most critical challenge: the spacecraft CoG estimation. The issue is directly related especially to the size of the tank, since larger tanks increase the uncertainty related to the amount of propellant remaining and the distribution in space, consequently the CoG estimation.
The issue becomes particularly evident during coasting phases, where liquid and gas, free from applied forces, can disperse and occupy volume in intricate solutions. The challenge is partially mitigated following an initial firing, when the liquid and gaseous phases are propelled by the acceleration. However, the initial transient phase poses a non-trivial challenge to resolve, strictly connected to the fourth bullet point.
If the system relies on a gas-fed engine, the fluid phase injecting in the thruster must be strictly controlled, since the event of liquid injection would result on a sudden increase of mass flow rate, causing possibly fatal damage to the combustion chamber structure, jeopardizing the overall mission. Contrary, a system based on liquid injection where a biphase flow is created can result in unstable and difficult to control combustion.

## VI. Conclusions

The new emerging class of spaceborne systems, hereby called Orbital Transfer Vehicles, carries the promise of facilitating access to space and unlocking new missions. The benefits could extend to private and public sectors, improving the overall utilization of space for existing and new players.
The emerging systems, many of which aim to cover a diverse range of missions, exert significant pressure on the current capabilities of in-space propulsion systems. This is particularly evident in the challenges related to cost reduction and the modularity of various solutions. Green propellants emerge as a promising solution to address these issues, offering the potential to lower costs and explore innovative systems that have not been previously considered.
The present study explored a specific class of propellants that have historically been discarded for the very feature that was used to select them for new systems: the high vapor pressure during storage at operating temperatures. This pressure can be utilized as inherent feeding pressure in the line, simplifying the system design by totally removing the pressurization system. The utilization of these propellants is attracting the interest of various private entities that are actively working on developments of technologies based on them.
By performing an overall selection, there are not many compounds that respect the strict requirements posed by the sector, safety, and mission requirements. The only available oxidizer applicable for the systems under investigation is nitrous oxide, a well-known compound commonly utilized in hybrid rockets. Between the fuels, only a few candidates appear applicable. Propylene and Ethane appear as ideal candidates for their physical properties, compatibility, and performance. The latter, ethane, is particularly promising for its very high vapor pressure and low performance sensitivity to oxidizer to fuel ratio shifts, allowing for more design freedom. The main drawback of the candidates is

their low density, especially ethane. The study did not examine the potential presence of external devices designed to increase the vapor pressure of the compounds, such as the utilization of heaters. This approach could potentially enhance the performance of promising candidates, such as ammonia.

The development of new propulsion systems based on these propellants necessitates the creation of relevant models that describe the overall behavior and evolution of critical parameters during the operation of the systems. Scientific literature offers numerous examples of models with increasing capabilities and complexity. However, these models are challenging to implement, and the improvement in predictions is often not significant enough to justify the increase in complexity. By instead utilizing relatively simple models capable of capturing sufficient detail to draw conclusions, it has been possible to study various effects of long firings of these engines. Some effects impose constraints on the maximum burning time, but with appropriate precautions, these limitations can be mitigated.

The decision on the draining phase from the tank is crucial for the stability of the thrust delivered by the engine. In the absence of an external pressurization system that controls and stabilizes the mass flow rates, the behavior of tank emptying, mass flow rate, and combustion chamber are intricately coupled. Despite this coupling, the challenges it presents are not insurmountable, and associated issues could be managed through robust and adaptable designs. Notably, the analyses suggest that choosing to extract liquid oxidizer instead of gaseous is one of the most crucial design considerations for achieving a stable thrust delivery and optimal performance.

In conclusion, the models, while approximations of the actual behavior of such systems, can be valuable assets in the early phases of development. Further validation of these models with finalized designs is essential, but significant uncertainties persist, especially regarding their performance in microgravity environments. The behavior of saturated fluids in microgravity is seldomly explored and challenging to predict.

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