# CONCEPTUAL STUDY OF SMALL PRESSURE-FED ENGINES

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**Abstract.** *This article presents the conceptual study of different designs of small pressure-fed liquid rocket engines which use storable, nontoxic propellants. The described configurations could serve for main propulsion of upper-stages or attitude control systems of rockets and launch vehicles. The analysis intends to be a preliminary discussion of alternative designs of upper-stage propulsion systems and reaction control systems of Brazilian rockets and launch vehicles. They could be taken as initial points for capacitation in the field of liquid propulsion. The study initiates with monopropellant systems based on the catalytic decomposition of hydrogen peroxide aqueous solution, which could be specially adequate to use as roll control system of VLS-1 vehicle. All other analyzed conceptions are bipropellant systems whose oxidizer is hydrogen peroxide solution, and the fuel is either kerosene, ethanol, or liquefied propane. The accomplished comparisons are basically of qualitative nature, although a simple quantitative analysis of the principal influences of propellant selection on the system performance had been done.*

**Keywords:** *Pressure-fed propulsion system, Rocket engine design, Reaction control system, Conceptual study, Preliminary design.*

## 1. INTRODUCTION

Small pressure-fed systems have large use in rockets, launch vehicles, and satellites, either as main propulsion systems in upper-stages, or as auxiliary propulsion systems of launch vehicles and spacecrafts. As reaction control systems (RCS), in particular, they can be used in solid, liquid, or hybrid launch vehicles.

Traditionally, these small engine systems are based on storable, toxic mono- and bipropellant systems. These preferences arose mainly from concerns related to the designing for maximum performance and minimum weight, instead of designing for minimum cost. However, the use of very toxic and hazardous (for both, environment and personnel) propellants must be avoided as much as possible and, in addition, currently cost is becoming one of the main concerns.

Rational design of a pressure-fed, propulsion system should use preferentially nontoxic, storable propellants. The system should be simple, reliable, safe to operate, and cheap (the development and fabrication costs should be low). The use of commercially available, off-the-shelf components should be routine. Launch and tests should use available facilities, or require low investment to construct new ones.

This article outlines some conceptual alternatives of small propulsion systems using nontoxic, storable propellants, conceived in accordance with the philosophy of minimum cost design, for further discussion and analysis. Concentrated hydrogen peroxide, commonly referred as high test peroxide or HTP, was selected to be used in all the conceptions: either as the unique propellant in monopropellant concepts, or as oxidizer in the bipropellant concepts.

The first alternative is a monopropellant system based on the catalytic decomposition of a hydrogen peroxide solution. All the other alternatives are bipropellant systems with hydrogen peroxide solution as oxidizer, and liquefied propane, kerosene, or ethanol as fuel. Some qualitative characteristics of each design option are given. The proposed configurations must be subject to detailed analysis, a posteriori, in order to evaluate their feasibilities and relative advantages/disadvantages.

## 2. STUDY DIRECTIONS

The ground rules for the study were stated within the design-to-cost methodology, taking into consideration safety and environmental constraints. Among other low cost development approaches, the following directions must be considered:

- Pressure-fed systems for RCS and upper-stage systems.
- Common, storable, nontoxic propellants.
- Expendable systems.
- Restarting capability.
- Pulsed regime of work for RCS configurations.
- Conservative design assumptions.
- Reducing component costs through adapting commercial manufacturing practices.
- Utilizing commercial off-the-shelf hardware.
- Maximize use of existing facilities and support equipment.
- Evolving low cost operations.
- Low cost thrust vectoring mechanisms or secondary injection thrust vector control (SITVC) for upper-stage systems.
- Cooling system: since regenerative cooling is associated with a large pressure drop in the cooling jacket, this type of thermal protection was disregarded. The remaining options are radiative cooling, ablative cooling, film cooling, and combinations of these methods.

## 3. PROPELLANT SELECTION

The nature and the proportion of the propellant components of a propulsion system influence its configuration and some of its main subsystems (Oliveira, 2000b). Therefore the choice of propellant combination is a very important task in the definition of the system. It must be done as early as possible, in order to account for its impacts on the system performance and cost.

The main drivers of propellant selection for the systems in study were stated in the previous section. The philosophy is to use the simplest propellant combination that will provide the necessary performance, satisfying technical, economic and ecological requirements.

There are only a few non-cryogenic, non-exotic liquid oxidizers available (Oliveira, 2000b): nitric acid (NA) derivatives (WFNA, IWFNA, RFNA, IRFNA), nitrogen tetroxide (NTO), nitrous oxide ($N_2O$), and hydrogen peroxide aqueous solution are the obvious choices. Of these, only hydrogen peroxide is nontoxic[1]. It has other advantages as well (Andrews, 1990). It is very dense and has a very low vapor pressure. It is relatively inexpensive because it is an ordinary industrial chemical rather than a dedicated rocket propellant (Jeff, 1998). It is a good regenerative coolant and has excellent characteristics to be used in secondary injection for thrust vector control. Although some special precautions must be taken to prevent it from decomposing

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[1] Rigorously, $N_2O$ is toxic only above 94% concentrations. In addition, $N_2O$ has self-pressurization capacity, an interesting advantage for use in pressure-fed systems.

in the presence of impurities, it is a stable substance, and once those precautions have been taken it essentially handles like water (Jeff, 1998).

Since HTP can be used as both an oxidizer and a monopropellant, a number of beneficial design simplifications and variable operational scenarios are possible. The decomposition products can be used as the oxidizer in a bipropellant system, for thrust in monopropellant mode, and as the working fluid for pressurization and turbine drive. The dual mode operation (mono- or bipropellant) enables wide thrust variability.

Given that the oxidizer was chosen, the next step is the fuel selection. Hydrazine and its derivatives (UDMH, MMH, etc.) form hypergolic mixtures with HTP, but are very toxic. Therefore, the hydrazine family is discarded. Among the alcohols, methanol is very toxic, and the obvious choice is the ethanol. The hydrocarbons that better meet the requirements are kerosene, liquefied propane, and liquefied petroleum gas (LPG). Among the kerosene types, the better options are JP-4, JP-5 and RP-1.

RP-1 is a specifically refined petroleum product particularly suitable as a rocket fuel. It is basically a mixture of saturated and unsaturated hydrocarbons with a somewhat narrow range of densities and vapor pressure. RP-1 is low in olefins and aromatics, because they can cause carbonaceous deposits inside fuel cooling passages.

JP-4 is the prime fuel now used for jet aircraft. It has a low vapor pressure and a low freezing point, and is designed with specifications which could be met by fuels available throughout the world. JP-5 is a narrow-range low-volatility fuel very similar to the standard rocket fuel, RP-1. Engines with regenerative cooling normally use the fuel as coolant. Then, for such engines, RP-1 is the kerosene-like fuel normally chosen, since its deposition on coolant channels is lower. However, if HTP — a very good coolant — were chosen as oxidizer, even in a regeneratively cooled engine, ordinary JP-5 rather than expensive RP-1 can be used as the fuel, because, in this case, the HTP would be used as coolant.

Propane ($CH_3CH_2CH_3$) is the most accessible of the liquid and gaseous alternative fuels. It is the main component of Liquefied Petroleum Gas, or LPG, which is a liquid mixture (at least 90% propane, 2.5% butane and higher hydrocarbons, and the balance ethane and propylene). It is a by-product of natural gas processing or petroleum refining. LPG, like natural gas and unlike gasoline, is a simple mixture of hydrocarbons. Compared to petroleum refining hydrocarbons it has highly reproducible thermochemical properties. The general properties of LPG and propane are very similar. However, since propane presents higher vapor pressure, it will be preferred for the applications in study.

Note that at room temperature propane could be not adequate to pump fed engines, as its vapor pressure is too high for light weight tanks. For such type applications, it could be used at its normal boiling point or at sub-cooled state, forming a good cryogenic pair with liquid oxygen (LOX).

Some consideration about handling propane. A tank rupture while a propane tank is being pressurized would release large quantity of propane. If not ignited by the rupture, this would rapidly vaporize and form a ground hugging flammable cloud, since gaseous propane is denser than air. In most cases, one believes however that the propane would be dispersed to non-flammable limits before leaving the pad security area. It is expected that this sort of problem is well studied and can be dealt with. Certainly, large quantities of propane are routinely transported by road and rail through cities and if this practice if not totally safe at least appears to be reasonably accepted.

Briefly, the selected oxidizer was HTP, and the fuels selected for further analysis were kerosene, ethanol and liquefied propane. The average mass density (bulk density) $\rho_\mathrm{p}$ and the combustion chamber temperature $T_\mathrm{c}$ (at chamber pressure $p_\mathrm{c} = 6\,\mathrm{bar}$) for bipropellant combinations of these components are shown in Fig. 1 ($K_\mathrm{m}$ denotes the mass mixture ratio). The corresponding parameters for the standard combination UDMH/NTO are also given in Fig. 1, for purpose of comparison.

The combustion process including hydrogen peroxide gives a relatively low adiabatic combustion temperature. This means reduced requirement for cooling the thrust chamber (small chambers are usually radiation-cooled).

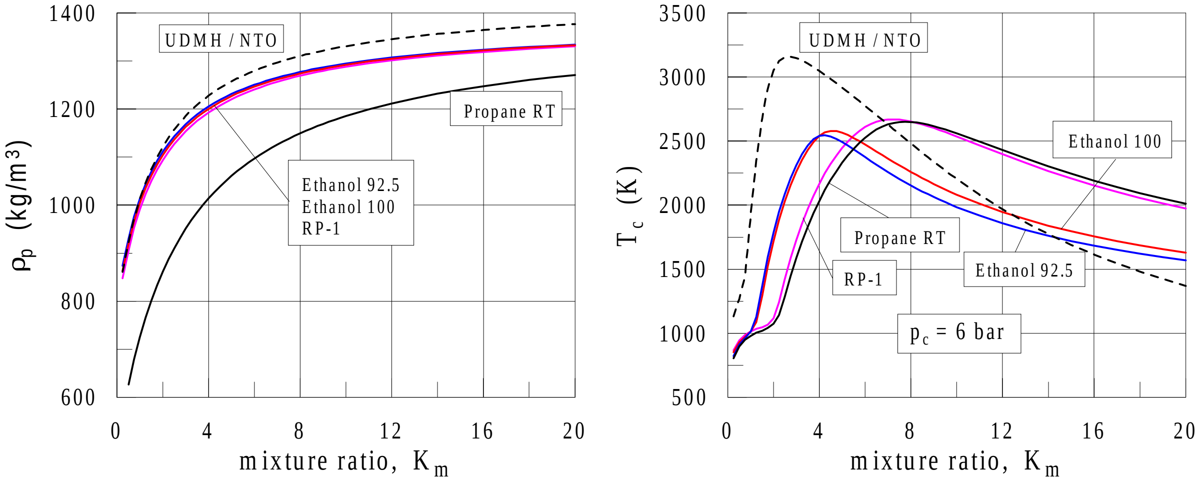


Figure 1: Average mass density of propellant and combustion chamber temperature for different mixture ratios and propellant combinations of HTP-90% and storable, nontoxic fuels.

The design impacts on the vehicle and ground support subsystems when the proposed propellant combinations are used must be better examined. At first, there are no significant cost difference between facilities to handle these several propellant components. There are no large propellant cost differences. Therefore, vehicle cost differences also are certainly negligible. No significant technical challenge exists for properly conditioning the vehicle propellant on the ground and in flight when heated propane is used as fuel.

## 3.1 Self-Ignition of Fuels with HTP

The stated requirements include restartability for upper-stage propulsion system and pulsed regime of work for RCS. To meet these requirements more easily, the selected propellant combination must be rendered hypergolic. This can be done in two ways.

The first method consists on catalytically decomposing the hydrogen peroxide to steam and oxygen before injection into the thrust chamber. Then, the fuel can be injected as a liquid into a high-temperature gas flow. It will ignite and burn spontaneously with the free oxygen of the decomposed hydrogen peroxide. This would yield superior combustion stability and permit easy throttling of the engine by adjusting the amount of fuel in the mixture. The effective life of the solid catalyst bed is another concern. This method is feasible for both the propulsion systems (main or auxiliary) using combinations of the selected propellants, as will be explained further.

The second method is to mix an additive into the fuel to make it self-ignitable with HTP. This makes it possible to adopt a unified system with improved mass and volume characteristics. The problem with solid catalyst-bed life can also be avoided. Thus, the development of a self-ignition system for HTP/fuel becomes enabling for its utilization for the studied propulsion systems. The basic issues for the fuel blend are that it must be homogeneous and nontoxic.

Early in the World War II period, the Germans developed fuels capable of self-ignition with HTP. The fuels used at that time were alcohols, such as Ergol 56 (62.5% methanol, 30% catechol, and 7.5% ferrous dialkyl naphthyl sulfonate) and C-Stoff (70% methanol and 30% hydrated hydrazine) (Andrews and Sunley, 1990). In addition to methanol, the catalyst and promoter accounted for about 40% of the mixture, which considerably affected the operation and energy characteristics of the propellant (Hurlbert *et al.*, 1998) and, must be remembered, methanol is rather toxic.

In Russia, similar research on nontoxic, hypergolic propellants is being pursued. In 1993, a research program on additives to kerosene that can self-ignite with HTP was initiated and test-firings on a low-thrust test thrust chamber were successfully conducted in China. This program is discussed by Hurlbert *et al.* (1998).

In the USA in the late 1940s, exploration of self-igniting fuels with HTP was also conducted, including kerosene drop-flow testing, and fuel additive selection (candidate catalysts included manganese sulfate, copper sulfate, sodium nitro-prusside, and potassium cuprocyanide mixed with hydrated hydrazine) (Kelley, 1947). Satisfactory results were not achieved at that time, but this exploration has been continuing, and recently gave some good results, as will be described next.

### Nontoxic Homogeneous Miscible Fuel

Airframe, Ordnance and Propulsion Division at the Navy's research facility in China Lake announced in August 1998 that its researchers have developed a nonpolluting rocket fuel that relies on alcohol for use with HTP. The Navy's "nontoxic homogeneous miscible fuel," or NHMF, suspends the catalyst in alcohol, which is then mixed with the hydrogen peroxide, igniting the reaction. The ignition takes less than 15 milliseconds. The Navy would not disclose the composition of the catalyst.

So far, China Lake researchers have used the liquid fuel in prototype missile thrusters built on a small scale. The works had continued in order to scale them up to flight-weight size to demonstrate their applicability. Already, major USA aerospace companies are talking to the Navy about the new fuel.

According to the available information, the Navy's NHMF is going to be a little bit lower-performing than the base fuel. Advanced formulations are being studied by Professor Rusek at Purdue University which actually exceed the performance of the industry standard NTO/MMH combination. Professor Rusek was the principal discoverer of NHMF, while with the United States Navy. Currently, his research works at School of Aeronautical and Astronautical Engineering (AAE) of Purdue University is aimed at studying the kinetics of ignition delay for this unique bipropellant combination, maximizing the energy density within this class of fuels, and in developing robust injector designs for usage in LREs. Recent hypergolicity testing at Pudue University reveals ignition delays less than 10 ms using the baseline NHMF formulation.

### Competitive Impulse, Non-Carcinogenic Hypergol

The Redstone Army Lab announced in February 2000 the development of a low-toxicity fuel that ignites on contact (hypergolic) with nitrogen tetroxide or inhibited red fuming nitric acid (IRFNA). Known as Competitive Impulse, Non-Carcinogenic Hypergol or CINCH, the new fuel has been in development since 1994, and is a safer all-purpose replacement for a wide variety of hydrazine and hydrazine-based fuels.

A recent test successfully demonstrated that the experimental fuel could be used in satellite launchers that use Aerozine-50, a carcinogenic hypergolic fuel. In 1998 CINCH was successfully tested in a monopropellant thruster. According to Redstone Lab, theoretical calculations also indicate that CINCH performs better than RP-1 with hydrogen peroxide or liquid oxygen.

Marshall Space Flight Center (MSFC) has conducted a preliminary evaluation of the fuel. Demonstration projects using hydrogen peroxide and liquid oxygen with CINCH are planned with Edwards Air Force Base and the MSFC. NASA plans to pursue the concept of using CINCH with several different oxidizers, and as a monopropellant in a satellite launch vehicle.

Unlike many developmental fuels, CINCH is commercially available. For example, 3M has a pilot plant producing CINCH to meet numerous requests from liquid propulsion developers.

# 4. CANDIDATE CONFIGURATIONS

## 4.1 HTP-Monopropellant Systems

Monopropellants provide inherently simple systems and are most suited to low total impulse systems, such as reaction control systems. Hydroxyl ammonium nitrate- (HAN-) based propellants, gaseous nitrogen mixed with low concentrations of oxygen and hydrogen, and hydrogen peroxide ($H_2O_2$) all provide viable solutions for nontoxic monopropellant propulsion systems. The current status of these propellants is discussed in (Hurlbert *et al.*, 1998).

The monopropellant systems, in the same way as the bipropellant ones, can be either pressure-regulated or blowdown types. Relative comparisons of these two basic types appear in several publications, e.g., in some works of Hearn (1980,1982, 1995). Three HTP-monopropellant systems will be analyzed in the following.

### Configuration M-1: HTP-Monopropellant Pressure-Regulated System

The first design conception is the HTP-monopropellant system shown schematically in Fig. 2. It is a traditional configuration of a stored-gas, pressure regulated system without heating. It consists of high-pressure storage tank (pressurant vessel), start and shutdown valve, pressure regulator, HTP tank, propellant valve, catalyst bed, and thrust chamber.

High pressure gas outflows from pressurant tank, after start/shutdown valve is opened, throttles in pressure regulator down to the feeding pressure, and enters the monopropellant tank. The HTP is expelled from its tank, passes by the propellant valve, and then is decomposed by the catalyst bed inside the decomposition chamber, as shown in Fig. 2. The decomposition products (steam and gaseous oxygen) are expanded in the nozzle, producing thrust. The most complex component of this system is the catalyst bed.

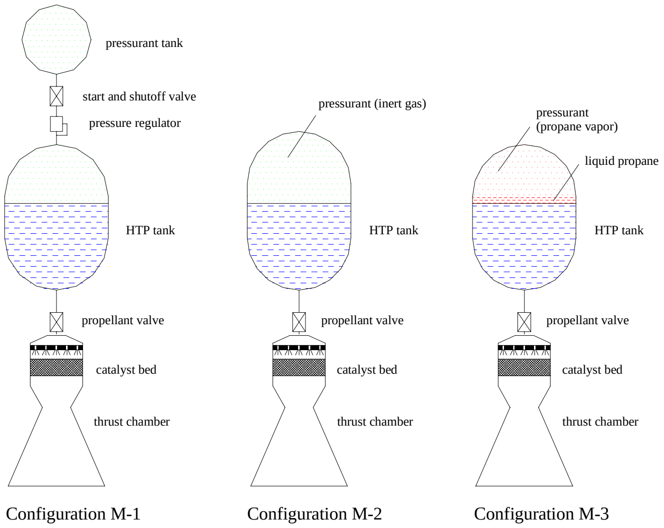


Figure 2: Monopropellant configurations.

### Configuration M-2: HTP-Monopropellant Blowdown System

A simple alternative to the pressure-regulated system represented by configuration M-1 is the blowdown system designed by configuration M-2, and illustrated also on Fig. 2. Here, the pressurant is stored directly inside the propellant tank, together with the HTP. Again, inert gases such as nitrogen or helium are used for pressurization. As the propellant is expelled, the pressurant expands and, consequently, the ullage and the feeding pressures decrease.

The tankage is considerably simpler than in configuration M-1, due to the absence of a separate pressurant vessel, pressure regulator, pressurization valve, and corresponding gas feedlines. All other components of this system are essentially the same as in the M-1 configuration.

### Configuration M-3: Propane-Pressurized System

In configuration M-3 (see Fig. 2), the pressurant is the saturated vapor of liquefied propane or of another light hydrocarbon, stored inside the HTP tank (in the upper part, since HTP is denser than liquefied propane).

During the HTP expulsion process, the evaporation of liquid propane decreases the temperature at the interface gas-liquid and, correspondingly, decreases the vapor pressure of propane. Therefore, there is a decline in the feeding pressure, but it is comparatively lower than in the pure blowdown system (Configuration M-2). In this way, the configuration M-3 combines regulated-pressure characteristics with the simplicity of pure blowdown systems.

The incompatibility between propane and HTP is a point of concern, and must be carefully investigated. Meanwhile, it is known that fuel-rich gases can be safely used for pressurization of oxidizer tanks (Huzel and Huang, Chapter 5, 1992). Some systems use positive-expulsion devices such as metallic or elastomeric diaphragms, and inflatable elastomeric bladders (Huzel and Huang, Chapter 8, 1992). In these cases, possible problems due to incompatibility of propane/HTP are eliminated, given that the direct contact these substances is avoided.

## 4.2 HTP-Bipropellant Systems

### Configuration B-1: HTP-Kerosene or HTP-Ethanol

This configuration is a bipropellant gas-liquid (G-L) system, as shown is Fig. 3. The oxidizer is HTP, which is decomposed in a catalyst bed before its injection into the combustion chamber. The fuel is kerosene or ethanol. The gaseous products of HTP decomposition (gaseous oxygen and water vapor) have enough high temperature to form a self-igniting mixture with kerosene or ethanol. Thus, the system presents the multiple-starting characteristics.

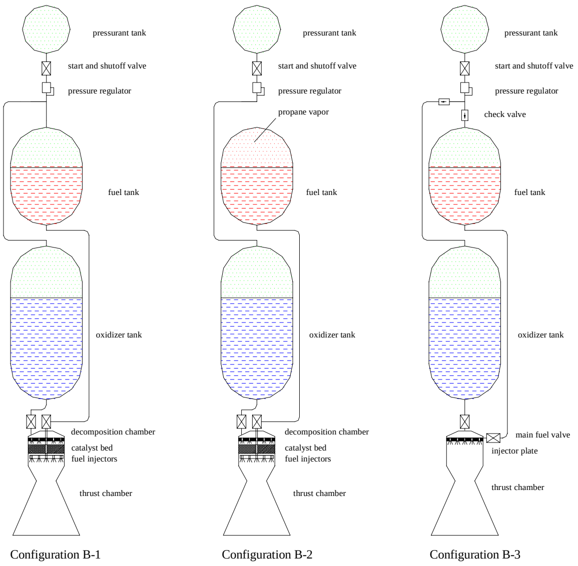
The HTP is fed through a solid catalyst bed consisting of impregnated wire screens. Since the specific impulse of decomposed HTP alone is low (below 2000 m/s, depending on concentration and design parameters), the fuel is injected below the decomposition chamber. Because of the high temperature of the decomposition gases, the fuel ignites and burns spontaneously with the free oxygen of the decomposed HTP. In this manner, the solid catalyst indirectly serves as an ignition system. While the specific impulse with the fuel afterburner is still moderate, such a system offers versatility, storability and simplicity, including the capability of throttling to low levels and restartability.

It's necessary to investigate if it can be used in pulsed regime of operation, since the time-lag between successive pulses could be larger than the desired ones. This could be a disadvantage in comparison with traditional hypergolic systems.

The catalyst bed is the most complex device of all devices of the system. However, it is rather easy to construct. Nowadays there are several different options that could be used (Davis and McCormick, 1960; Rusek, 1998).

### Configuration B-2: HTP-Propane

Configuration B-2 is an innovative system also shown on Fig. 3. It's a gas-liquid (G-L) or a gas-gas (G-G) system, depending on the chamber pressure and if the propane is heated or not, before its injection into the combustion chamber.



Configuration B-1 Configuration B-2 Configuration B-3

Figure 3: Bipropellant configurations.

The oxidizer tank is pressurized by gaseous helium (He) or nitrogen ($N_2$). The fuel tank is self-pressurized due to the special characteristics of propane at its use temperature. For use in a RCS, in particular, this configuration could use nitrogen (instead of helium) as pressurant for the HTP tank. This choice means higher pressurant mass, but lower requirements in terms of tightness and cost of equipments and manufacture (valves, regulators, weldings, etc.). Moreover, nitrogen is cheaper and available everywhere.

The HTP is decomposed in a catalyst bed, and the decomposition products (gaseous oxygen and steam) are burned with the liquid or gaseous propane inside the combustion chamber. It's hoped that the oxidizer-fuel mixture be self-igniting. Therefore, the system could work with multiple ignitions as, for example, in a pulsed regime of operation.

This configuration represents a very simple and reliable system. The use of storable (non-cryogenic), nontoxic, non-corrosive propellants permits the use of cheaper off-the-shelf components (valves, regulators, feed-lines, etc.). The ecologically clean nature of the propellants and its burning products, and the almost harmless effects of accidental spills or leakage, increase the safety of the system.

At end of operation, remains some residual fuel in form of vapor (and, eventually, in form of liquid) in the fuel tank. This residual mass of fuel must be taken into account during the design calculations.

The fuel tank is greater than that one of previous configuration, since both kerosene or ethanol are denser than liquefied propane, and the residual mass in the tank at end of operation, in this case, could be higher than in configuration B-1. In the other hand, the pressurant vessel should be shorter than that in configuration B-1 (Fig. 3), since there both propellant tanks must be pressurized by this external gas.

Again, the most complicated device is the catalyst bed. Note that the temperature of combustion products in combustion chamber is approximately the same for configurations using kerosene and propane, which, in turn, are greater than those using ethanol (see Fig. 1).

### Configuration B-3: HTP-Kerosene-M or HTP-Ethanol-M

This configuration is a liquid-liquid (L-L) system. It is also illustrated in Fig. 3. The oxidizer is again HTP, which is injected in liquid phase (without decomposition) inside the combustion chamber. The fuel is a homogeneous blend of kerosene or ethanol with some additive. This blend forms a hypergolic mixture with HTP. This way, the system has the multiple-ignition characteristics, and could be used as pulsed system, like in a reaction control system.

The problem with catalyst bed doesn't exist any more, since it is absent. The main concern with this conception is the choice of the proper additive to form the fuel blend with desired properties. In order to find good blends there are a lot of research mainly in USA and China. In USA, particularly, two interesting blends (NHMF and CINCH) are available, as discussed during the propellant selection.

This system is comparatively simpler than the configurations B-1 and B-2, although demands some caution due to the hypergolic characteristics of the propellant combination. Any way, it is very reliable and safe, given that be found a proper fuel blend.

## 4.3 Performance of Bipropellant Systems

For comparative analysis for the influence of different propellant combinations on the mass-performance of a main propulsion system it is convenient to break-down the total mass of the system ($m_{\mathrm{s}}$) as follows (Oliveira, 2000c):

$$m_{\mathrm{s}} = m_{\mathrm{pl}} + m_{\mathrm{pe}} + m_{\mathrm{pr}} + m_{\mathrm{tkg}} \, .$$

Here, $m_{\mathrm{tkg}}$ denotes the *tankage mass*, which comprises the pressurant mass $m_{\mathrm{g}}$, the pressure vessel mass $m_{\mathrm{pv}}$, and the masses of the fuel $m_{\mathrm{tf}}$ and oxidizer $m_{\mathrm{to}}$ tanks. The terms $m_{\mathrm{pe}}$ and $m_{\mathrm{pr}}$ stand for the expelled (useful) and residual propellant masses, respectively.

All the other masses of the system are included on *gross payload mass* $m_{\mathrm{pl}}$: includes all elements of rocket vehicle mass not primarily determined by the propellant selection, i.e., net payload, guidance system, control system, stage structure, and rocket engine mass.

The main influence of different propellant combinations can be evaluated by comparing the payload capabilities on the "common denominator" of equal initial vehicle mass, velocity increment, and propellant storage and expulsion subsystem design criteria.

The mass-performance criterion chosen for a main propulsion system is a propellant payload fraction parameter (Oliveira, 2000c),

$$M \equiv m_{\mathrm{pl}}/m_{\mathrm{s}} = \left(m_{\mathrm{s}} - m_{\mathrm{pe}} - m_{\mathrm{pr}} - m_{\mathrm{tkg}}\right)/m_{\mathrm{s}} \, .$$

The mass-performance of auxiliary propulsion systems is given in terms of the ratio of total impulse to system mass (Oliveira, 2000c). For the propellant combinations in study, the results show qualitatively the same behavior as the mass-performance of main propulsion systems. The volume-performance of an auxiliary propulsion system can be evaluated by the density-impulse ($I_{\mathrm{d}}$) obtained with the propellant combination (Oliveira, 2000c).

Figure 4 presents the mass and volume performances for main and auxiliary bipropellant propulsion systems, respectively $M$ and $I_{\mathrm{d}}$. These data were obtained using the procedure and program described in (Oliveira, 2000c). The configuration B-1 was used for all the propellant combinations. The shown results indicate that all the proposed propellant combinations have almost equivalent mass-performances. For limited-volume applications, however, propane shows a rather worse performance than kerosene.

These curves show only the main tendencies, since secondary effects of propellant selection on the system performance were not considered. Therefore, the inclusion of these secondary effects could change the relative performances. For example, it was disregarded the pressure vapor of propane during the estimation of the total pressurant requirement of the combination propane/HTP. If the self-pressurization characteristics of propane were considered in the mass-performance evaluation, the combination propane/HTP could give better result than the kerosene/HTP combination.

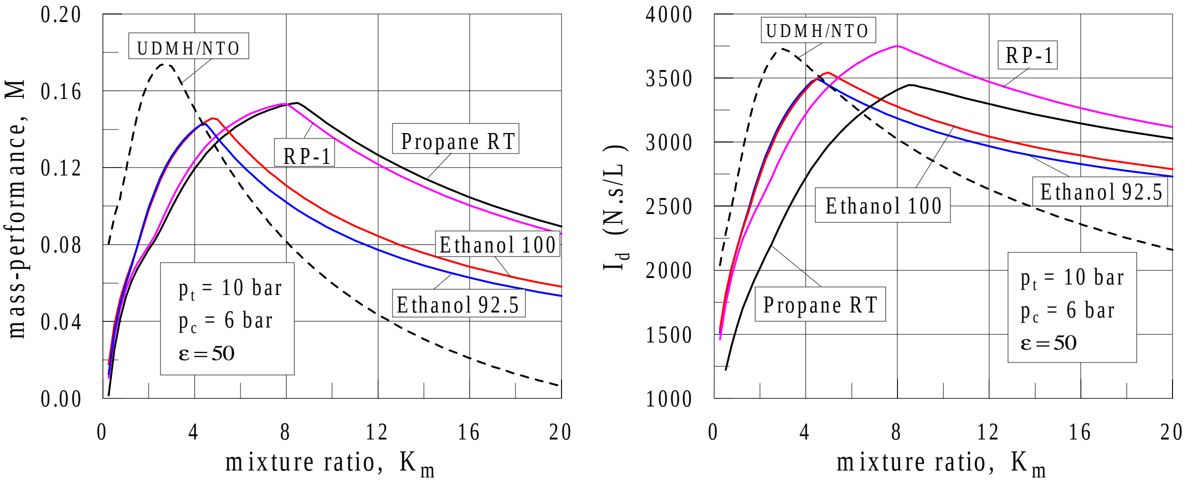


Figure 4: Mass- and volume-performance at different mass mixture ratios for main and auxiliary bipropellant propulsion systems.

In comparison with the UDMH/NTO combination, the nontoxic combinations show lower mass-performance (see Fig. 4). But, if the secondary effects of propellant on the total system were included, the verified differences tend to reduce. As example, can be pointed out the consequences of its significantly higher combustion temperatures on the thrust chamber cooling (see Fig. 1). Thus, in an ablatively protected chamber, the mass of the ablative liner will be lower for the relatively amenable thermal environment resulting for the analyzed nontoxic propellant combinations.

## 4.4 General Comments

In configurations where the HTP is catalytically decomposed, the most complex component of the systems is the catalyst bed. Traditionally, macroscopic metallic screens and coated ceramic pellets have been used as catalysts for the decomposition of hydrogen peroxide as applied to monopropellant thrusters, liquid rocket engines, and hybrid rocket systems (Davis and McCormick, 1960). Catalyst activity depends on available catalytic surface area; elemental catalysts can be severely degraded by oxidation under use conditions. New approaches to forming robust, highly active and stable decomposition catalyst systems for flightweight applications were discussed by Rusek (1996). More recently, Rusek (1998) discussed the synthesis, characterization, and evaluation of high surface area catalyst beds, and made comparisons with traditional propulsion catalysts.

The monopropellant configurations are more adequate to auxiliary systems. In the other hand, the bipropellant configurations can be used either for auxiliary or for main propulsion systems. Booster and first-stage of launch vehicles are normally single-starting, and use external ignition system. Therefore they could be considerably simpler than multiple-ignition systems.

There are some other variants of the presented systems to be analyzed. For example, the pressurization using the decomposition products of HTP produced by HTP-monopropellant gas generator could be advantageous for second stages of launch vehicles, and should be considered in trade-off studies (Oliveira, 2000a).

The self-pressurization capability of propane is rather versatile. It could be heated up to proper temperature in order to attain the desired pressure. For example, at room temperature (27° C) the vapor pressure is approximately 10 bar, and at 38° C the vapor pressure is about 17 bar.

In all the discussed alternatives could be investigated the possibility of use liquefied propane as the pressurant for all the selected propellants. The propane should be stored directly inside the propellant tanks, in the same way as in the fuel tank of configuration B-2. This type of pressurization introduces some advantages of blowdown systems in the pressure-regulated systems. Possible problems due to incompatibility of propane/HTP could be eliminated in different ways. First, avoiding the direct contact between theses substances by using an inflatable bag. It could be used in main or auxiliary propulsion systems. Note that in systems using a positive-expulsion device (bladder or diaphragm) the physical isolation is already ensured. Second, adding some inert gas in order to form in ullage a mixture out of flammability limits.

The monopropellant blowdown systems (configurations M-2 and M-3) are the simplest of all the presented configurations. They are particularly interesting for gain experience in the field of liquid propulsion. Therefore, besides their usefulness as practical systems, they could be used as starting systems for study and development of more complex mono- and bipropellant ones.

It's needed researches for the proper design of G-G, G-L and L-L injectors for the candidate propellant combinations used in conceptions B-1, B-2 and B-3.

It's suggested begins the development of catalyst beds for use in monopropellant systems as in configurations M-1, M-2 and M-3, and bipropellant systems like configurations B-1 and B-2.

Another front of research is to find the additive for the fuel blend that will form a good hypergolic combination with HTP. The obtained fuel blend should present some important properties: nontoxic, storability, non-corrosive, good stability, homogeneous mixture, low sensitivity to impact and shock, and low-cost. In addition, the additive should preferentially available in Brazil.

## 5. CONCLUSIONS AND ADDITIONAL SUGGESTIONS

This study outlines some conceptual design options of small engine systems to be submitted to discussion and further evaluations. All concepts are nontoxic, storable propellants, pressure-fed systems. They could be adopted in RCS's or in upper-stages of rockets and launch vehicles. Besides environment friendly, the propellants are cheap and available in Brazil.

The monopropellant configurations based on catalytic decomposition of HTP are simple and reliable, but have low specific impulses. Therefore, they should be destined to use in auxiliary propulsion. The other configurations analyzed are bipropellant systems with HTP as oxidizer, and propane, kerosene or ethanol as fuels. Since restarting capability is a essential requirement for the intended applications, two bipropellant configurations use decomposition of HTP before injection into combustion chamber (G-L systems), and one configuration uses a fuel blend that forms a self-igniting mixture with the non-decomposed HTP (L-L system).

The more innovative conception uses liquefied propane (stored at ambient temperature) and HTP decomposed catalytically, forming singular L-G or G-G systems, depending on if the propane is vaporized before its injection into the combustion chamber. Differently of all other configurations which use stored-gas pressurization systems for all the propellant tanks, this case uses that type of pressurization only for the oxidizer tank: the fuel tank is self-pressurized by gaseous propane (at room-temperature). In a variant of this conception, propane could be used as pressurant for both the fuel and oxidizer tanks.

All the analyzed configurations are potentially feasible for the present technical and technological capacities of the Institute of Aeronautics and Space (IAE). Moreover, they are safe, inexpensive, environment benign, meet the requirements to be used in low-cost vehicles, and could be developed and produced in short-run with the available resources of IAE. However, detailed quantitative analysis must be carried out before discards or any additional comparisons and choices. Thus, until better information be available, all these design conceptions should be considered by IAE, either as initial point of liquid propulsion development, or as alternatives to the roll control system currently used in the VLS-1 launch vehicle.

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