STUDY OF PROPELLANTS FOR PRESSURE-FED PROPULSION SYSTEMS

Ulisses Côrtes Oliveira — E-mail: ulisses@iae.cta.br
Instituto de Aeronáutica e Espaço — ASE-E/IAE/CTA
12228-904 — São José dos Campos–SP, Brazil

Abstract. *This paper presents a discussion about the adequate propellant selection for pressure-fed propulsion systems for use in launch vehicles. The type and the proportion of the components in a bipropellant combination affects the main subsystems of the vehicle. Therefore, its choice depends on the particular application of the propulsion system, and must be made early during the system requirement phase. The study approaches the more relevant aspects of the problem, and the resulting information serves as a first screening of candidate propellants to be used in detailed trade-off studies. The main conclusion is that the proper choice of nontoxic, storable, and high density-impulse propellants could produce reliable vehicles and harmless operations to personnel and environment, in addition to lower pre-operational and recurrent costs.*

Keywords: *Rocket propellants, Propulsion systems, Pressure-fed engine, Rocket engines, Launch vehicle design.*

1. INTRODUCTION

The present paper resumes part of a study to analyze alternative conceptions of pressure-fed launch vehicles of micro and small launch capacities. The approach is to develop low-cost vehicles using restricted technical capacities and available technologies, looking for taking advantage of previous experience in solid rocket propulsion, and maximizing the use of the existing ground installations for test and launching. This philosophy of Minimum Cost Design lead to pressure-fed propulsion systems in which are minimized the system development and recurring costs.

Once that the propellant feed system had been selected to be of pressure-fed type, the next most important choice is the propellant combination. The type and mixture ratio of propellant components will determine the shapes and relative positions of tanks, the pressurization and the cooling systems, and will affect the attitude control system and other minor subsystems of the vehicle. The propellant type influences also the configurations of ground facilities for testing and launching (Sutton, 1992, Chapter 5).

A variety of factors have resulted in increasing interest in the exploration of alternatives to the widely employed cryogenic and hypergolic propellant combinations. These factors include heightened sensitivity to cost, environmental concerns, and the personnel hazards associated with toxic propellants. Further driving the move toward other propellants is the realization that absolute performance in terms of specific impulse is not, for many applications, the most appropriate metric for selecting a propulsion system. Recent advances in material, structural, and manufacturing technologies allow the system designer the flexibility to employ nontraditional propellant combinations to develop an really low cost, commercially feasible system (Anderson et al., 1998).

Several studies (Kendrick and Dergarabedian, 1969; Hudson and Hunter, 1987; Anderson et al., 1998) have indicated that in order to achieve significant reductions in cost, future launch and space systems require specific and significant improvements in technology and design-to-cost methodologies. Some of the system studies have shown that in order to achieve commercial viability, expendable or reusable launch vehicle concepts require low cost main and auxiliary propulsion systems. These systems must be nontoxic, storable, throttleable, and must have a high density-impulse (Andrews, 1990; Frazier and Moser, 1995; Clapp and Hunter, 1993). In addition, simple and reliable restartability is essential for upper-stage and auxiliary propulsion systems (Hurlbert et al., 1998; Frazier and Moser, 1994).

This paper is specifically concerned with the adequate propellant selection of pressure-fed propulsion systems for use in launch vehicles. The more relevant aspects of the problem are discussed, and the study results serve as a first screening of candidate propellants, being useful during the conception and trade-off studies and the early design definitions. Therefore, final choices of propellant combination must be accomplished with the help of more detailed tools, at more advanced steps of the design process.

2. LIQUID PROPELLANT COMPONENTS

There have been many extensive investments in research of propellants over the last six decades (Palaszewski, 1997). Most of these ideas related to propellants were abandoned, due to different reasons. Inasmuch, only a few propellants — composed by carbon, hydrogen, oxygen and nitrogen (C, H, O, N) — continue to be used nowadays.

In the other hand, while operational usage has not yet come to fruition, at least five major areas have been identified for prosperous research: monopropellants, alternative hydrocarbons, gelled hydrogen, metallized gelled propellants, and high energy density propellants (Palaszewski, 1997). Numerous studies have shown the potential benefits of this new generation of fuels and oxidizers (Palaszewski, 1997).

Discussions of the characteristics of several common liquid propellant components and their safety concerns are presented in (Sutton, 1992), (Huzel and Huang, 1992) and (Barrère et. al., 1960). Physical properties and a more complete discussion of the subject is given by Sarner (1966). The toxicity of some propellants affects the pre-operational and operational costs, is harmful to personnel, and causes damages to the environment. Therefore, the use of such propellants in circumstances where they could be easy substituted by others less aggressive is rather irrational, and must be avoided as much as possible (Oliveira, 2000a).

The following tables present some common fuels and oxidizers of interest for this analysis, after a preliminary analysis discussed by Oliveira (2000a). Nontoxic propellants, besides other important properties, would be much safer in the vicinity of human operations. So, it was only included nontoxic propellants, and were ignored exotics like boranes. Hydrazine family and nitrogen oxides are very toxic and, at first, deserve of further analysis. However, UDMH and NTO were included for purpose of comparison. Nitrous oxide (N_2O), although not included in the present discussion due to lack of space, has some interesting properties for the intended applications, in spite of its relatively low oxygen content (Oliveira, 2000a). It is relatively unreactive, moderately corrosive and toxic[1], self-pressurizing (vapor pressure higher than 50 bar at room temperature), etc. The data were collected from Sutton (1992), Huzel and Huang (1992), Barrère et al. (1960), Constantine and Cain (1967), and several other sources listed in (Oliveira, 2000a).

The properties shown in Tab. 1 are: $\mathcal{M}$, molar mass; ρ, mass density; T, temperature;

[1]It is toxic only above 94% concentrations.

Table 1: General data of some liquid propellant components.

Propellant component	$\mathcal{M}$ kg/kmol	FP K	NBP K	ρ (T) kg/m^3 (K)	H_v kJ/kg	c_p (T) cal/g-K (K)	μ (T) centipoise	p_v (T) bar (K)
LH_2	2.016	13.94	20.39	71 (NBP)	446	2.31 (NBP)	0.0131 (NBP)	2.026 (23)
Methane	16.03	90.5	111.6	445 (93.1)	510	0.835 (NBP)	2.0 (93.1)	0.33 (100)
Propane-RT	44.094	85.47	231.10	570 (298)	370	0.616 (293)	0.115 (293)	10 (300)
Propane-BP	44.094	85.47	231.10	582 (NBP)	426	0.535 (NBP)	0.209 (NBP)	1.01 (NBP)
Propane-SC	44.094	85.47	231.10	782 (100)	—	0.468 (123)	1.341 (123)	—
RP-1	175	225	460–540	807 (289)	246	0.45 (298)	0.75 (289)	0.02 (344)
JP-4	128.0	213	405–516	747 (295)	—	0.50 (298)	0.722 (298)	0.50 (344)
Ethanol-92.5	41.25	150.4	350.9	810 (295)				0.90 (289)
Ethanol-100	46.06	158.65	351.45	785 (295)	838	0.62 (293)	1.25 (293)	0.059 (293)
UDMH	60.08	216	336	789 (295)	584	0.649 (298)	0.49 (300)	0.130 (289)
Water	18.02	273.15	373.15	1000 (293)	2553	1.008 (273)	1.000 (277)	0.0689 (312)
LOX	32.00	54.4	90.0	1142 (90.4)	213	0.4 (65)	0.19 (90.4)	0.052 (88.7)
HTP-90%	31.286	261.65	414.25	1387 (298)	1629	0.663 (298)	1.158 (298)	0.0044 (298)
HTP-95%	32.571	267.54	419.15	1414 (298)	1574	0.645 (298)	1.160 (298)	0.0035 (298)
HTP-98%	33.424	270.65	421.55	1431 (298)	1541	0.633 (298)	1.158 (298)	0.0031 (298)
HTP-100%	34.016	273.50	423.7	1442 (298)	1523	0.626 (298)	1.153 (298)	0.0028 (298)
IRFNA	55.90	214.81	313.15	1564 (293)		0.414 (298)	1.37 (298)	0.241 (298)
WFNA	59.90	231.6	355.7	1460 (295)	480	0.418 (298)	0.779 (298)	0.605 (343)
NTO	92.016	261.95	294.30	1447 (293)	413	0.367 (290)	0.423 (293)	0.958 (293)

H_v, heat of vaporization; c_p, specific heat at constant pressure; μ, dynamic viscosity; p_v, vapor pressure. FP and NBP denote freezing and normal boiling temperatures, respectively. RT means room temperature, and SC means subcooled state. The tabled values of H_v are measured at the NBP temperature, except for Propane-RT, Propane-SC, UDMH and HTP-100% (298 K).

Tables 1 and 2 include: liquid hydrogen, LH_2; methane, CH_4; propane, C_3H_8, at room temperature (RT), normal boiling point (NBP), and subcooled (SC); RP-1, $CH_{1.923}$; ordinary jet fuel JP-4, $C_{9.66}H_{19}$; 92.5% and anhydrous ethanol, CH_3CH_2OH; unsymmetrical dimethylhydrazine (UDMH), $(CH_3)_2NNH_2$; water, H_2O; liquid oxygen (LOX), O_2; concentrated hydrogen peroxide (H_2O_2), commonly called high test peroxide or HTP; inhibited red fuming nitric acid (IRFNA); white fuming nitric acid (WFNA); and nitrogen tetroxide (NTO), N_2O_4. Water was included only for comparison.

Table 2: Handling, safety and cost of some liquid propellant components.

Propellant component	Stability	Handling hazard	Storability	Corrosion	USA Cost US$/kg
LH_2	Good	Flammable	Highly cryogenic	–	14.00
Methane	Good	Flammable	cryogenic	None	0.15
Propane-RT	Good	Flammable	storable	None	0.20
Propane-BP	Good	Flammable	cryogenic	None	0.24
Propane-SC	Good	Flammable	cryogenic	None	0.24
RP-1	A.I. 243°C	Flammable	Good	None	0.26
JP-4	Good	Vapor exp	Good	None	0.20
Ethanol-92.5	Good	Flammable	Good below 55°C	None	0.30
Ethanol	Good	Flammable	idem	None	0.40
UDMH	Good	Toxic	Good	Slightly cor.	1.00–4.00
Water	Good	Good	Good	None	0.00
LOX	Good	Good	cryogenic	None	0.08–0.10
HTP-90%	Dec. 140°C	Flammable	Good	Corrosive	0.80
HTP-95%	idem	Flammable	Good (1%year)	Corrosive	1.00
HTP-98%	idem	Flammable	idem	Corrosive	2.00
HTP-100%	idem	Flammable	idem	Corrosive	–
IRFNA	Good	Toxic	Good	Corrosive	0.16–0.20
WFNA	Dec. 38°C	Toxic	Fair	Very cor.	0.30
NTO	Func. Tem	Very Toxic	Good (dry)	Corrosive	0.15

The cost of a propellant component depends on the availability, quantity and several other factors. So, the given values must be seen only as rough estimates. Note that the cost of solid propellants runs about US$14/kg versus an average of about US$0.25/kg for liquids.

3. PROPELLANT TYPE, COMPOSITION AND PERFORMANCE

In a bipropellant propulsion system, the fuel and oxidizer components can be combined in different ratios to meet the specified propellant mixture properties.

The *propellant mass mixture ratio* (K_m) is the ratio at which the oxidizer and fuel are mixed and react to give hot gases, i.e., the ratio of the oxidizer mass flow rate to the fuel mass flow rate. It defines the composition of the reaction products and it is usually chosen so that it permits the attainment of maximum value of $T_c/\mathcal{M}$, where T_c is the combustion temperature and $\mathcal{M}$ is the average molar mass of the reaction gases, since the effective exhaust velocity $c \sim \sqrt{T_c/\mathcal{M}}$ (Sutton, 1992). Given the thrust F and having the exhaust velocity c, the total propellant mass flow rate $\dot{m}_p$ is obtained from the equation relating these two parameters, namely, $\dot{m}_p = F/c$.

For any given mixture ratio K_m, the *average mass density*[2] of a propellant combination ρ_p can be determined from the mass density of the fuel ρ_f and of the oxidizer ρ_o. It is defined as the mass of the fuel and oxidizer, divided by the sum of their volumes (Sutton, 1992, pag. 247):

$$\rho_p = (K_m + 1)\left(\frac{K_m}{\rho_o} + \frac{1}{\rho_f}\right)^{-1} .$$

The selection of the propellant combination is a compromise of many parameters, some of which are listed below (Barrère et al., 1960):

- Economic: availability in large quantities, low cost, logistics of production, simplicity of production process.
- Performance: specific impulse (or, equivalently, effective exhaust velocity), specific propellant consumption, high energy content, low molar mass, mass density, density-impulse.
- Common physical hazards: corrosive effects, explosive hazards, fire hazards, toxicity.
- Desirable physical properties: low freezing point, high mass density, chemical stability, high specific heat, high thermal conductivity, high boiling point, low viscosity, low vapor pressure.

Concerns about freezing point and pressure buildup in storage are basically those of a missile engineer, not a launcher engineer. A missile engineer wants something he can seal into the tanks of a missile that will be left on the shelf for years, bolted to the outside of an aircraft, flown for two hours in subzero stratospheric conditions, and then fired. A launcher engineer can make less drastic assumptions. In particular, it's no big deal to provide venting for tanks.

For high performance, a high content of chemical energy per unit of propellant mixture is desirable because it permits a high chamber temperature. A low molar mass of the product gases of the propellant combination is also desirable. It can be accomplished by using fuels rich in combined hydrogen, which is liberated during the reaction. A low molar mass is obtained if a large portion of the hydrogen gas produced does not combine with oxygen. In general, therefore, the best mixture ratio for many bipropellants is not necessarily the stoichiometric one (which results in complete oxidation and yields a high flame temperature) but usually a rich mixture containing a large portion of low-molar-mass reaction products. The above statements reflect the traditional approach which consists on pursuing a high performance in terms of specific impulse, without concerns about cost and development time.

[2] This term is preferable to the normally used *bulk density*, although the better designation would be *average volumic mass*, in accordance with the most recent recommendations (Taylor, 1995).

The performance of propellants can be compared on the basis of the effective exhaust velocity (specific impulse), the characteristic exhaust velocity, the specific propellant consumption, or other engine parameters, as discussed in (Sutton, 1992) and (Oliveira, 2000a). The effective exhaust velocity is function of pressure ratio, specific heat ratio, combustion temperature, mixture ratio, molar mass of combustion products, and engine configuration.

It is important, in propellant selection, to keep in mind that the usual absolute performance in terms of specific impulse ($I_{\rm sp}$) is not, for many applications, the most appropriate metric for selecting a propulsion system. The specific impulse is a property of the propellant mixture and of the engine configuration. It represents basically a energetic feature of the propellant, without associating any volumetric sense of a particular mixture.

In order to accommodate a large mass of propellants in a given vehicle tank space, a dense propellant is required. It permits a small vehicle construction and, consequently, a relatively low structural vehicle mass and low aerodynamic drag. Propellant mass density, therefore, has an important effect on the maximum flight velocity and range of any rocket-powered vehicle or missile flying within the earth's atmosphere, as explained in Flight Dynamics ordinary text books (see also (Oliveira, 2000a)).

Taking into account the above facts, it is concluded that the product of the average mass density $\rho_{\rm p}$ and the effective exhaust velocity c of the propellant combination, the so called density-impulse ($I_{\rm d} \equiv \rho_{\rm p}\, c$), is probably, for many applications, a more useful parameter.

Denoting the propellant volume by $V_{\rm p}$, and the system burnout mass by $M_{\rm e}$, for small $\rho_{\rm p}\, V_{\rm p}/M_{\rm e}$ such as that obtained in the first stage of a launch vehicle, as shown in (Oliveira, 2000a), the rocket equation can be approximated by

$$\Delta v = I_{\rm d}\, V_{\rm p}/M_{\rm e}\ ,$$

where Δv is the vehicle velocity increment. This indicates that, for a first stage where the propellant volume to final mass ratio is fixed, the stage's performance is mainly determined by $I_{\rm d}$, and not just by c alone. In fact, this approximation is valid for a number of propellant combinations and $V_{\rm p}/M_{\rm e}$ ratios (Oliveira, 2000a). That is, a propellant's density is just as important as its exhaust velocity in the booster or in the first stage of a rocket. For the second and higher stages, the exhaust velocity is much more important, since it significantly affects $M_{\rm e}$.

As shown by Oliveira (2000a), the density-impulse can be interpreted as a measure of the total impulse delivered per unit volume of the propellant. Thus, for $I_{\rm d}$ = const, $I_{\rm t} = I_{\rm d}\, V_{\rm p}$. This means that, for a fixed propellant volume $V_{\rm p}$, the propellant mixture with higher $I_{\rm d}$ delivers higher exhaust velocity and thus, makes it attractive for applications where size is a essential factor.

Calculated performance values in terms of effective exhaust velocity and density-impulse, for a number of different propellant combinations and at chosen mixture ratios and combustion chamber pressure $p_{\rm c} = 20$ bar, are given in Tab. 3. The thermochemical analysis was performed by using the CETPC program (1994), assuming shifting equilibrium expansion. The given mixture ratios are the optimum for maximal effective exhaust velocity c, except for LH_2 which is calculated at the mixture ratios of 4.00 and 5.55 (the first value gives a higher c, but it is associated to a much poorer average mass density). Here, c^a and $I_{\rm d}^a$ are for $A_{\rm e}/A_{\rm t} = 4.5054$, $p_{\rm c}/p_{\rm e} = 25.000$, $p_{\rm e} = 0.8000$ bar; and c^b and $I_{\rm d}^b$, for $A_{\rm e}/A_{\rm t} = 100.00$, $p_{\rm c}/p_{\rm e} = 1610.97$, $p_{\rm e} = 0.01241$ bar. These conditions could be representative of main propulsion systems (particularly, of a first stage or booster).

The more important result in Tab. 3 is the behavior of the propellant LH_2/LOX relative to the other propellant combinations. It presents the highest c of all the propellant combinations, mainly due to lowest average molar mass of its combustion products. But, at same time, it shows the lowest $\rho_{\rm p}$ and $I_{\rm d}$ values.

Figure 1 shows the variations of the average mass density and combustion temperature of propellants at different mixture ratios. In this case, the combustion temperature was calculated

Table 3: Theoretical data of some interesting liquid propellant combinations.

propellant		K_m	ρ_o	ρ_f	ρ_p	$\mathcal{M}_p$	T_c	c^a	I_d^a	c^b	I_d^b
oxidizer	fuel		kg/m^3	kg/m^3	kg/m^3	kg/kmol	(K)	m/s	Ns/L	m/s	Ns/L
LOX	LH_2	4.00	1149	71	284	9.96	2901	3472.6	987	4457.5	1267
LOX	LH_2	5.55	1149	71	346	12.60	3290	3388.7	1172	4447.1	1538
LOX	Methane	3.00	1149	424	805	20.19	3332	2709.5	2181	3576.0	2878
LOX	Prop.-BP	2.70	1149	581	909	21.61	3431	2665.4	2422	3535.5	3213
LOX	RP-1	2.60	1149	773	1012	23.11	3503	2611.7	2644	3489.5	3532
LOX	Ethanol	1.50	1149	789	972	22.18	3194	2515.9	2445	3300.9	3208
HTP 100%	Ethanol	4.00	1442	789	1237	21.59	2805	2395.2	2964	3146.5	3893
HTP 100%	RP-1	7.50	1442	773	1309	22.21	2883	2415.8	3162	3208.2	4199
HTP 98%	RP-1	7.50	1429	773	1299	22.15	2857	2406.9	3127	3195.1	4151
HTP 95%	RP-1	7.50	1411	773	1286	22.04	2816	2391.2	3075	3165.2	4071
HTP 90%	RP-1	7.50	1380	773	1263	21.83	2734	2349.0	2968	3083.7	3896
HTP 85%	RP-1	7.50	1352	773	1243	21.55	2621	2286.8	2841	2986.8	3711
WFNA	RP-1	4.00	1527	773	1278	24.05	2961	2291.0	2927	2979.4	3807
IRFNA	RP-1	4.80	1480	773	1278	25.40	3045	2313.7	2958	3048.1	3897
NTO	RP-1	4.30	1431	773	1233	25.86	3323	2407.8	2969	3216.6	3966
NTO	UDMH	2.65	1431	783	1167	23.47	3294	2504.6	2922	3314.5	3866

at $p_c = 6\,\text{bar}$, a value characteristic of upper-stage and auxiliary propulsion systems. The mass density curve must be analyzed with care, if not it could induce to wrong conclusions.

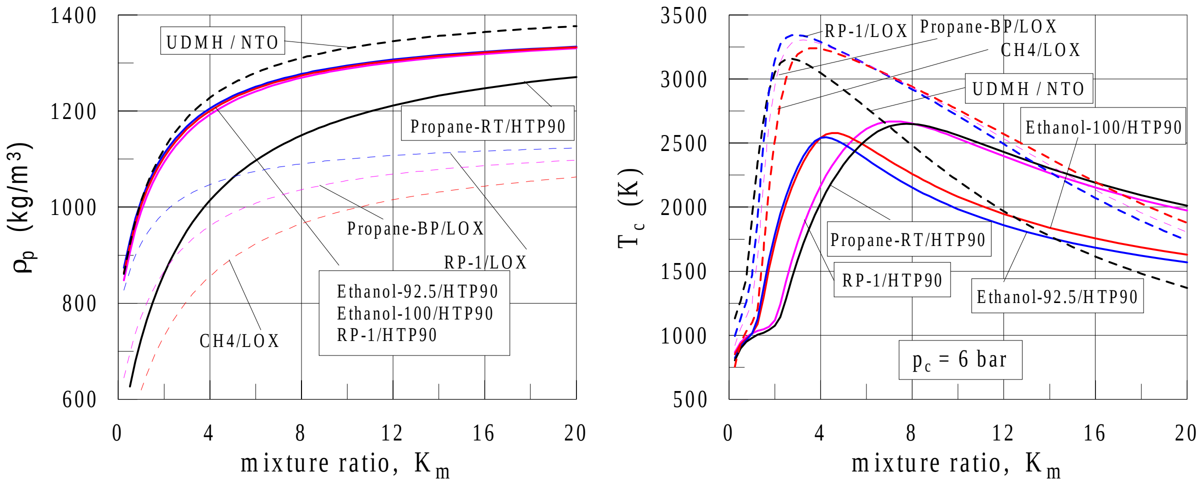

Figure 1: Average mass density and combustion temperature of different propellant combinations.

From Fig. 1 and Tab. 3 become evident the more affordable thermal environment of the propellant combinations whose oxidizer is HTP.

4. PROPULSION REQUIREMENTS AND PROPELLANT SELECTION

Exists a variety of propulsion requirements in terms of application (booster, first-stage, upper-stage, attitude control, etc.), total impulse, and thrust level. These are the main drivers of propellant selection for main and auxiliary bipropellant propulsion systems. But, as seen previously, the choice of propellants for a propulsion system must take into account, besides the particular type of application, availability, cost, previous experience in use the propellants, environmental restrictions, health hazards, etc.

In terms of main propulsion system, for specified propulsion thrust, pressures at chamber and nozzle exit, and feed system scheme, the impact of effective exhaust velocity and mass density of a propellant on the vehicle characteristic velocity depends on propellant type. So, its preferable to utilize a propellant with higher mass density on the lower stage. On the following stages, the influence of the mass density decreases, but the effective exhaust velocity become more important.

In the other hand, auxiliary propulsion systems such as a Reaction Control System (RCS) are generally low thrust ones, and the principal concern is the effect of propellant on their total impulse (I_t), within constraints of mass or volume.

Pressure-fed systems have some peculiarities which exert important influences in the propellant choice. First, the total pressure drop through feedlines, valves, regulators, and coolant passage channels in a cooling jacket must be as low as possible in order to not be necessary very high tank pressure, since this could increase the inert mass fraction of system. Second, the necessity to reduce the pressure difference between the propellant tanks and the combustion chamber could exclude the possibility of regenerative cooling in all the thrust chamber, being necessary to use alternative heat protection: radiation, ablative, film cooling, or combinations of these alternatives. This fact implies in the preference of propellant combinations which produce lower combustion temperatures. Third, if a high vapor pressure is bad for pump-fed systems, in the pressure-fed systems this could be an advantage, given that the vapor pressure reduces and even so dispenses the mass requirement of external pressurant (self-pressurization possibility).

Table 4 suggests bipropellant combinations for launch vehicle applications. The systems are supposed pressure-fed systems, and the philosophy is to use the simplest propellant combination that will provide the necessary performance, satisfying the technical specifications, and economical and environmental restrictions. Note that monopropellant and cold-gas systems, particularly adequate to use in auxiliary propulsion, were not included in Tab. 4 neither in the present analysis.

Table 4: Suggested bipropellants for different applications.

oxidizer	fuel	booster	first-stage	upper-stage	RCS
LOX	LH_2			x	
LOX	methane	x	x	x	
LOX	propane	x	x	x	
LOX	kerosene	x	x	x	
LOX	ethanol	x	x	x	
HTP	kerosene	x	x	x	x
HTP	ethanol	x	x	x	x
HTP	propane	x	x	x	x
NA	kerosene	x	x	x	
NA	propane	x	x	x	
NTO	kerosene	x	x	x	

A number of alternate fuels have been proposed for use with liquid oxygen, but only nontoxic candidates were preliminarily selected: LH_2, methane (or liquefied natural gas, LNG), propane (or liquefied petroleum gas, LPG), kerosene or ethanol.

LH_2/LOX offers the highest effective exhaust velocity of any realistic chemical propellant option. It also offers a relatively high oxidizer/fuel mass ratio, and several off the shelf engines are available. The primary disadvantage of LH_2/LOX is the very low density of hydrogen, which creates the need for large volume tanks which are difficult to incorporate into a reasonable airframe design, and which also creates tankage mass penalties that counter much of the benefit of LH_2/LOX's high c. An additional disadvantage is the necessity to handle the very cryogenic hydrogen, which stores at 20 K, and is not available to support vehicle operations in many parts of the world, including Brazil.

CH_4/LOX offers the second highest c, with the benefit of a great increase in propellant density over LH_2/LOX (CH_4 is six times as dense as LH_2), allowing tankage sizes and masses to be brought under control. The CH_4/LOX mixture mass ratio is approximately 3.5, and while both CH_4 and LOX are moderately cryogenic, they both store at the same temperature (around 90 K) so that compact tankage arrangements are possible. Liquid methane is available in most places around the world. In fact, CH_4/LOX is by far the cheapest rocket propellant combination that there is; so that if the launch vehicle operations were to expand to the point where fuel costs were an important factor, this would be a real plus.

Kerosene/LOX offers a high effective exhaust velocity and a rather dense propellant combination, only one of whose components is cryogenic. From the several types of kerosene, RP-1, JP-4 and JP-5 are the more interesting for this study. While RP-1 (a rocket engine grade kerosene) is a refined, expensive and not so common kerosene, JP-4 (ordinary jet fuel) is cheap and available at airports everywhere. JP-5 is a narrow-range low-volatility fuel very similar to the RP-1. In comparison with JP-4, it is denser and also available everywhere. In spite of other better properties of RP-1, JP-4 and JP-5 are more common and cheaper alternatives.

Propane ($CH_3CH_2CH_3$) is the most accessible of the liquid and gaseous alternative fuels. It is the main component (at least 90%) of Liquefied Petroleum Gas, or LPG. Compared to petroleum refining hydrocarbons it has highly reproducible thermochemical properties. With LOX, propane could be used heated, at room temperature, at its normal boiling point, or yet at subcooled state. Subcooled propane (at LOX temperatures or slightly above) has a mass density nearly the same as that of kerosene, and a superior c, and its use with LOX could, at first, generate vehicles with very low total dry mass. Certainly, propane and kerosene fuels result in lower vehicle dry mass than methane and LH_2. When heated or at room temperature, propane present self-pressurization capability as a very attractive feature for pressure-fed engines.

Ethanol/LOX is less energetic than the hydrocarbons/LOX combinations. However, it gives cleaner combustion and relatively amenable thermal environment in the thrust chamber. Ethanol is cheap and available in Brazil in large amounts.

Concentrated hydrogen peroxide (HTP) and ethanol, kerosene or liquefied propane make an attractive Earth-storable bipropellant combinations. The big advantage of these propellant combinations is that they are entirely noncryogenic, so that the required land facilities for launch and test and almost all the vehicle subsystems will be much less involved than for the propellant combinations whose oxidizers are LOX. HTP in concentrations in the range of 85–98% are most applicable to liquid-propulsion systems. HTP is storable, has a high density, is a good regenerative coolant, has excellent characteristics to be used in secondary injection for thrust vector control. These features, allied to the possibility of to be used also as monopropellant, make it an option for different applications (Andrews, 1990). A rather complete discussion of these combinations of storable fuels with HTP is given in (Oliveira, 2000a).

Combustion temperature and mass- and volume-performance of several propellant combinations for combustion chamber pressure $p_c = 6\,\text{bar}$, tank pressure $p_t = 10\,\text{bar}$ and expansion area ratio $\varepsilon = 50$ are shown in Fig. 2. The chosen mass-performance criterion is measured in terms of (M), the ratio of the gross payload mass to the system mass (Oliveira, 2000b). In this case, the gross payload mass includes all the masses not primarily determined by the propellant selection, i.e., net payload, guidance system, control system, stage structure, and rocket engine mass. The chosen figure of merit for volume-performance comparison is the density-impulse (I_d). The shown values correspond to mass mixture ratios at maximum values of M, for each bipropellant combination. Fig. 2 shows that the storable combinations produce lower combustion temperature, and have better performance in applications with limited propellant volume.

The characteristics of various bipropellants are summarized in Tab. 5 as they relate to criteria important to main and auxiliary propulsion systems (Oliveira, 2000a). These are all relative comparisons of the propellant combinations for each given criterion. A plus symbol indicates that the system is desirable or advantageous for that criterion relative to the other systems, and a negative symbol indicates a disadvantage of the system compared with the others, with respect to that criterion. The final selection of a propellant depends on the relative importance of each criterion to a particular application.

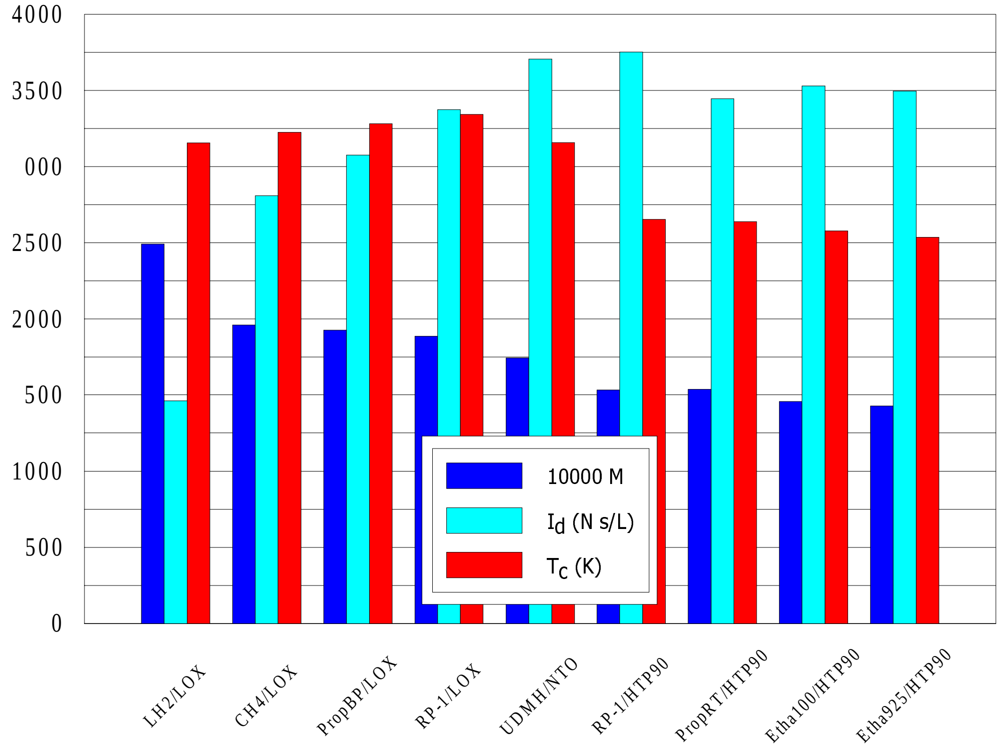

Figure 2: Comparison of the performance of several propellant combinations ($p_c = 6$ bar, $\varepsilon = 50$).

Here and in Tab. 5, NA denotes generically nitric acid (HNO_3). It was omitted in Tab. 5 the combination NTO/kerosene, which presents essentially the same relative characteristics of NA/kerosene, although NTO is more expensive, less corrosive, more toxic and less dense than NA.

In a comparison of candidate propellant combinations for different propulsion systems, factors in addition to mass and volume, such as toxicity, may become important and must be taken into account. Toxicity affects the cost of operation and maintenance. The main advantages of nontoxic propellants, besides the potentially lower pre- and operational costs, are their environmental friendliness and harmlessness to personnel.

A ranking among candidate propellant combinations could be made using an analytical hierarchy process with conveniently chosen relative weights for toxicity, cost, mass, volume, and

Table 5: Evaluation of bipropellants for the proposed applications (relative each other).

oxidizer ⟶	LOX					HTP			NA
fuel ⟶	LH_2	methane	propane	Kero	ethanol	Kero	ethanol	propane	Kero
Propellant mass performance, c	+	+	−	−	−	−	−	−	−
Volume performance, I_d	−	+	+	+	+	+	+	+	+
Inert (dry) mass	−	−	−	+	+	+	+	+	+
Number of components	−	−	−	+	+	+	+	+	+
Integration with power	+	+	+	+	+	−	−	−	−
Thermal management	−	+	+	−	−	+	+	+	+
Residues and soot	+	+	+	−	+	+	+	+	−
Materials (corrosivity, temper.)	−	+	+	+	+	−	−	−	−
Leakage	−	+	+	+	+	+	+	−	−
Number of required instruments	−	−	−	+	+	+	+	+	+
Number of flight operations	−	−	−	+	+	+	+	+	+
Toxicity	+	+	+	+	+	±	±	±	−
Propellant cost	−	+	+	+	+	−	−	−	+
Flammability	−	+	+	+	+	+	+	+	+

other attributes. Some of the combinations with assigned higher scores could be used in further detailed analysis in order to achieve the final selection. It should be pointed out that the choice of the relative weights is somewhat arbitrary and should be based on the needs of the particular application. Any way, for the present purposes, the storable combinations with HTP as the oxidizer tend to give higher scores.

Ordinarily, propellants and pressurants are a relatively insignificant part of the cost of a launch vehicle. Because of the overall very low system cost, this may be not the case for Minimum Cost Design pressure-fed systems. Consequently, the use of kerosene and LOX at approximately US$0.26/kg and US$0.08/kg, respectively, must be considered with special care. Moreover, these components are readily available, environmentally friendly and have been used successfully for several years.

5. CONCLUSION

From the several rocket liquid propellants analyzed and tested during the last decades, most never were used in practical applications, and only a few propellants continue to be used nowadays. Curiously, propane and methane never were considered as they should have been, and hydrogen peroxide has been generally dismissed without rational considerations.

The propellant combination affects almost all subsystems of the launch vehicle, and also the configurations of ground facilities for testing and launching. Therefore, it affects all the related — development and operational — costs, and its choice is made early during the system requirement phase.

Using adequate propellants can lower operations cost, simplify launch vehicle processing, and make space flight more accessible and affordable. Other capabilities that are enabled with these adequate propellants allied to proper technologies are better vehicle cooling, reduced vehicle structural mass, reduced thermal protection requirements, improved safety, and higher reliability.

Certainly there is no one ideal propellant in existence which combines all the many desirable qualities. Indeed, some of them are contradictory, such as high density and high effective exhaust velocity. So, in any concrete case, where the application of a propulsion system is specified, it becomes necessary, therefore, to pick out this or that quality as being predominant for the particular purpose in view and to choose the propellant accordingly.

Low-cost pressure-fed propulsion systems, in particular, have some important peculiarities in terms of cost, tank pressurization, thrust chamber cooling, etc., which drive the propellant selection.

Among the potential oxidizers, LOX and HTP are the more interesting for the present applications. However, due to its storability, very high density, and very low cost, nitric acid (particularly, IWFNA) could be considered in some circumstances, given that its toxicity and corrosiveness can be tolerated. Nitrous oxide was not included in the present discussion, but it is storable, only moderately corrosive and toxic, and self-pressurizing. So, it also should be considered a candidate in the analysis of a practical propulsion system.

Considering only nontoxic components, the better candidate fuels are LH_2, methane, propane, kerosene and ethanol. LH_2, in spite of its very good energetic and environmental characteristics, was disregarded due to its highly cryogenic and low density nature, as well as due to its high price and restricted availability. In combinations with LOX, it could be substituted, with several advantages, by methane or propane, in some cases, or by kerosene or ethanol, in other cases.

The use of a cryogenic propellant implies in a series of technological difficulties. They are not long term storable, need special thermal protections, and present other disavantages that normally are traduced in cost.

For lowest development and operational costs, launch-on-demand applications, a propellant combination that is storable and environmentally clean must be considered with interest. Combinations of kerosene, propane, or ethanol with hydrogen peroxide have these key features as well as others which make them ideal choices for low-cost, expendable or reusable, propulsion systems. These propellant combinations are not the most energetic available, but they are extremely inexpensive and among the easiest of rocket propellants to design for and to operationally handle. In addition, these propellant choices favor the use of commercial off-the-shelf components and lead to less complex systems. Simplification will also reduce the total number of launch vehicle parts, which will in turn enhance the system's overall reliability.

The most promising storable combination is propane/HTP, due to the self-pressurization feature of propane, which can be tailored to different pressure levels, by heating. Propulsion systems using such combination, if extremely simple in design, can take better advantage of manufacturing and operating economies of scale due to the ease of inspection and the relatively lower cost of propellant.

The results of this paper serve as a first screening of candidate propellants to be used in detailed trade-off studies of pressure-fed propulsion systems, in the context of the design-to-cost philosophy. Specific analyses of the effect of a particular propellant on the cost and performance gains for various missions are dependent on the vehicle and mission design. Ultimately, before designs are finalized, a complete parametric study of the system should be made resulting in optimization with reference to the particular mission involved.

Acknowledgments

The author wish to express his gratitude to Mauro Kochi Yamamoto for manuscript revision and useful discussion on the subject.

REFERENCES

Anderson, W.; Bender, M.; Crockett, D.; Hill, S.; Lewis, T., Fuller, R.; Morlan, P.; Ruttle, D.; Wu, P.-K.; and McNeal, C., 1998, "Low Cost Propulsion Using a High-Density, Storable, and Clean Propellant Combination." *1st International Hydrogen Peroxide Propulsion Conference*, July 29–31, Surrey University, England.

Andrews, D., 1990, "Advantages of Hydrogen Peroxide as a Rocket Oxidant," *Journal of the British Interplanetary Society*, Vol. 43, July, pp. 319–328.

Barrère, M. et al., 1960, "Rocket Propulsion," Elsevier, New York.

Clapp, M. D., and Hunter, M. W., 1993, "A Single Stage to Orbit Rocket with Non-Cryogenic Propellants," AIAA Paper 93-2285.

Constantine, M. T.; and Cain, E. F. C., 1967, *Hydrogen Peroxide Handbook.* Technical Report AFRPL-TR-67-144, Chemical and Material Department, Research Division, Rocketdyne.

Frazier, S. R., and Moser, D. J., 1994, "Low Cost Liquid Upper Stage for Small Launch Vehicles," AIAA Paper 94-3024, 30th Joint Propulsion Conference.

Frazier, S. R., and Moser, D. J., 1995, "Low Cost First Stage for Small Launch Vehicles," AIAA Paper 95-3088, 31th Joint Propulsion Conference.

Hudson, G. C. and Hunter II, M. W., 1987, "Liberty: A Low-Cost, Commercial Expendable Launch Vehicle." AIAA Paper 87-1794.

Hurlbert, E. A., et al., 1998, "Nontoxic Orbital Maneuvering and Reaction Control Systems for Reusable Spacecraft," *Journal of Propulsion and Power*, Vol. 14, No. 5, September-October.

Huzel, Dieter K.; and Huang, David H., 1992, *Modern Engineering for Design of Liquid Propellant Rocket Engines.* AIAA, Washington.

Kendrick, J. B.; and Dergarabedian, P., 1969, "Low Cost Launch Vehicle Study." Contract No. NASW-1794. TRW Report 11858-6008-R0-00.

Oliveira, U. C., 2000a, *Study of Propellants for Pressure-Fed Propulsion Systems.* IAE Internal Report, Instituto de Aeronáutica e Espaço, S. J. Campos, Brazil (to be divulged).

Oliveira, U. C., 2000b, *Computer Program to Evaluate the Mass-Performance of Storable Propellant, Pressure-Fed Systems.* IAE Internal Report, Instituto de Aeronáutica e Espaço, S. J. Campos, Brazil (to be divulged).

Palaszewski, B., 1997, *Propellant Technologies: A Persuasive Wave of Future Propulsion Benefits (A White Paper).* NASA Glenn Research Center.
(Site: http://www.grc.nasa.gov/WWW/TU/launch/Propellant.htm)

Program CETPC, Version 2.0. (See *CET93 and CETPC: An Interim Updated Version of the NASA Lewis Computer Program for Calculating Complex Chemical Equilibria With Applications.* NASA TM-4557, 1994.)

Sarner, S. F., 1966, *Propellant Chemistry*, Reinhold Pub. Co., New York.

Sutton, George P., 1992, *Rocket Propulsion Elements – An Introduction to the Engineering of Rockets.* John Wiley & Sons, New York.

Taylor, B. N., 1995, *Guide for the Use of the International System of Units (SI).* NIST Special Publication 811, 1995 Edition. U.S.A. National Institute of Standards and Technology.