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CHEMICAL PROPULSION ALTERNATIVES FOR BRAZILIAN ROCKETS

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Abstract. *This is a study of the more convenient propulsive alternatives for the Brazilian indigenous launch vehicles, based on the local technical and economical reality and on the main goals of the Brazilian Space Program. The study commences with a classification and a review of the main characteristics of the chemical propulsion systems used in aerospace applications. Then, together with non-technical aspects, the main technical advantages and disadvantages of the different systems are discussed. It is shown that aspects such as technical and technological capacity, previous experience, existing facilities for test and launch, availability of financial resources, and future pretensions must be accounted for the selection of propulsion type and propellant combination to be used for. Finally, it is recommended the development of pressure-fed liquid propulsion systems, which can permit to create simpler and cheaper vehicles, and could propitiate the necessary capacity for using hybrid propulsion and liquid pump-fed systems.*

Keywords: *Chemical Propulsion, Rocket Engines, Airbreathing Engines, Solid Propellants, Liquid Propellants, Hybrid Propellants, Rockets, Launch Vehicles.*

1 INTRODUCTION

The present study was motivated by the debate that took place after the accident occurred at the Alcântara launching center, when an engine of the Brazilian launch vehicle VLS-1 ignited unexpectedly, during integration tests, causing the destruction of all the vehicle and also of its launch pad. In the days following to the accident, much of that was said and/or written about the "Brazilian Space Program", in general, and in special way about the VLS-1 project, portrayed with certain allegiance their real situation. However, some opinions shown in the media lack, at least, of technical endorsement. In true, and for sadness of those whom see strategic and economic importance to in that program, not more than one ten of Brazilians could emit sound judgments and trustworthy opinions on the subject in question. Moreover, when moving exclusively to technical field, this number falls for less than a half ten of Brazilians.

In particular, a subject widely discussed at that time was the possible inadequacy of solid propulsion for the VLS-1. Among some opinions, it seems to have itself formed a consensus of that this type of propulsion would be outdated. But this idea is questionable, as will be shown later.

Many of the technical aspects and historical drivers of the national space program escape from the knowledge of most public and scientific community. This way most of opinions and critics are baseless.

The present study deals with an analysis of the more convenient propulsive alternatives for the Brazilian indigenous launch vehicles, having for base, above of everything, the local technical and economical reality and the main goals of the Brazilian Space Program. The study begins with a classification and a review of the main characteristics of the chemical propulsion systems used in aerospace applications. Then, other non-technical aspects are discussed, with the objective to add some information and basement to debate of the subject.

2 CHEMICAL PROPULSION SYSTEMS

Chemical propulsion systems for launch vehicles are primarily divided into two categories: *monopropellant* and *bipropellant* systems. In a monopropellant system the propellant is catalytically or thermally decomposed into a gas mixture, which is further expanded to produce thrust. In the other hand, in a bipropellant system the idea is to combine two substances, a fuel and an oxidizer, in some mixing region. The chemical energy associated with combining these two substances is transferred to the total flow as thermal (kinetic) energy. This high-energy flow can then be expanded out a nozzle to provide thrust for the attached vehicle.

Bipropellant systems are classified as *rocket engines* and *airbreathing engines*, as shown in Fig. 1. These differ in where oxidizer for the fuel is obtained from. Rocket engines use oxidizer carried on board the vehicle, while airbreathing engines obtain oxygen from the atmosphere. It is thought that use of airbreathing engines will reduce the amount of onboard oxidizer that must be carried and allow payload to be increased.

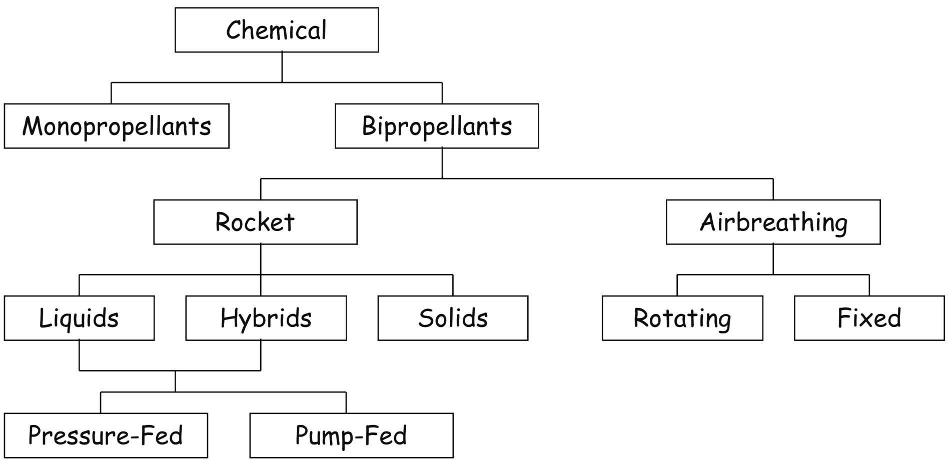

Figure 1: Chemical Propulsion Systems.

Airbreathing engines can be further divided into two sub-categories, namely engines *with rotating parts* (e.g. turbojet engines) and those *without rotating parts* (e.g. ram/scramjet engines). A ramjet operates by adding fuel to a stream of air compressed by the forward speed of the aircraft itself. Because the compressed air is hot, the fuel ignites and hot gases escape rearward, propelling the craft at speeds up to Mach 5. Scramjet is short for "supersonic-combustion ramjet." A scramjet is a ramjet engine in which the airflow through the whole engine remains supersonic, making speeds faster than Mach 20 possible.

Rocket engines are classified in accordance with the type of used propellant: *liquid*, *solid*, *hybrid*. Liquid-fuelled rocket engines can also be categorized in accordance with the type of propellant feed system: *pump-fed* or *pressure-fed*. In turn, the pump-fed ones are classified into several types (engine cycles) according to the energy source used to drive the turbines of the turbopumps.

In the next four subsections solid, liquid, hybrid, and airbreathing chemical systems are described more deeply, including their working principles, main differences and possible applications.

2.1 Solid Propulsion

Solid rockets are the oldest form of rocket propulsion, invented over eight centuries ago by the Chinese for use in fireworks. In solid rocket motors, fuel and oxidizer are chemically premixed to form a solid fuel grain. By simply igniting this substance, the oxidizer and fuel in the solid react and produce the high-energy combustion gases desired. A variety of designs for the central burning port of the solid fuel can be created so as to produce the desired thrust performance. Solid rockets provide good thrust and are one the most simple systems available. Solids can deliver high liftoff thrust needed by large launch vehicles, because they can produced very large mass flows more easily than liquids (Andrews and Haberman, 1991). On the down side, they also are fairly inefficient fuel burners and cannot be throttled. In some cases there may also be explosion dangers since the oxidizer and fuel are not separated.

2.2 Liquid Propulsion

Liquid rockets are somewhat different in nature, but also have a specific set of advantages and drawbacks. Liquid rockets utilize liquid fuel and liquid oxidizer stored in tanks. By either pressure feeding (pressure-fed systems) or by mechanically pumping (pump-fed systems) the propellants from their tanks, they are forced into a mixing chamber where chemical combustion occurs. These types of systems generally provide good thrust and can be thrust-controlled (throttled). In addition, they tend to be the most efficient of high-thrust engines. However, the complexity of these systems is also high. There are stop-valves, pressure regulators, injectors, turbopump machinery and all sorts of "plumbing". When considering that there needs to be redundancies on all of these systems in order to make a reliable system, it is easy to see that the overall cost and weight of liquid rockets could be excessive. In addition, due to the liquid nature of the propellants involved, there can also be storage problems.

There are several classical pump-fed engine power cycles. The *gas generator cycle* (and other "open cycles") is the least complex of the pump-fed cycles, but it also generally delivers the lowest performance. An open cycle denotes that the working fluid used to drive the turbine is exhausted overboard, or discharged into the engine well downstream of the nozzle throat. The *expander cycle* and the *staged combustion (or preburner) cycle* represent pump-fed systems having a more complex "closed cycle," but they provide higher performance. A closed cycle denotes that the exhaust from the working fluid that drives the turbomachinery is injected into the engine combustion chamber to take advantage of its remaining energy. There is little doubt that pump-fed propulsion systems are the most indicated for liquid boosters when the main concern is maximum performance and minimum weight, regardless of the type of turbopump engine cycle chosen.

Alternatively, pressure-fed propulsion systems offer the potential for greatly simplified designs of engines and overall vehicles (Huzel and Huang, 1992). Pressure-fed propulsion is most applicable to expendable launch vehicle designs, as main or auxiliary propulsion systems. Pressure-fed systems are almost certainly impractical for single-stage-to-orbit concepts, but they could be used in strap-on booster applications or in lower and upper stages of a multi-stage launcher. Table 1, adapted from (London III, 1999), compares pump-fed and pressure-fed engine cycles. For purpose of this generalized comparison, the several pump-fed classical cycles

Table 1: Liquid Engine Cycle Comparison.

	Pump-Fed		**Pressure-Fed**
	Gas Gener. Cycle	Complex Cycles[a]	
Vehicle weight[b]	1.25	1.0	1.75
Chamber pressure	55 to 100 bar	140 to 280 bar	15 to 20 bar
Specific Impulse[c] ($N \cdot s/kg$)	3000 (LOX/RP-1) 4000 (LOX/LH_2)	3200 (LOX/RP-1) 4300 (LOX/LH_2)	2800 (LOX/RP-1) 3800 (LOX/LH_2)
Tank wall thickness[b]	1.0	1.0	2.0 to 2.5
Tank pressurization system required	Yes, low pressure system	Yes, low pressure system	Yes, high pressure system
Tank pressure	2 to 3.5 bar	2 to 3.5 bar	35 to 50 bar
Vehicle complexity	2.5	4.0	1.0
Engine component part count[d]	2,000 to 3,000	5,000 to 7,000	100 to 200
Manufacturing complexity[b]	2.0	3.5	1.0

[a] Staged combustion and expander cycles. [b] Normalized dimensionless units. [c] Average I_{sp} through flight. [d] Major component parts.

are simply identified as "gas generator cycle" or "complex cycles."

The primary justification for the use of turbomachinery has been that turbopumps significantly increase the delivery pressure of the propellant as it is being routed to the rocket engine. The pressure of the propellant delivered to the engine combustion chamber injector is one factor that establishes combustion chamber pressure — and combustion chamber pressure is an important element in determining a rocket engine's physical size and, at lower extent, specific impulse (the higher the pressure, the higher the specific impulse). Engineers seeking compact, high performance engines want high chamber pressures with the attendant high performance turbomachinery. Using turbopumps to boost propellant pressures makes it possible to keep pressures in the large propellant tanks relatively low, allowing the tanks to have thin structural skins and be lightweight. The launch vehicle is intended to perform a task that is in direct opposition to the force of gravity, so vehicle designers have traditionally sought to keep the weight of the vehicle as low as possible. The use of turbomachinery has been key to this effort.

A launch vehicle that uses tank pressurization as opposed to turbomachinery to deliver propellant at the appropriate pressure to the engine combustion chamber injector is called a pressure-fed booster. The propellant must be pressurized by a high-pressure gas source or some other mechanism to a level that exceeds the required pressure at the combustion chamber injector. Compared to pump-fed boosters, a pressure-fed design exhibits structurally stronger (usually thicker-walled) propellant tanks, as well as engines that operate at lower chamber pressures (and have a lower specific impulse). Consequently, a pressure-fed booster with the same payload capacity to low-Earth orbit as a comparable pump-fed vehicle would be heavier and would need larger engines with greater thrust to compensate for the heavier dry gross vehicle weights and the lower engine efficiency (London III, 1999). Typical *propellant fraction* values (propellant mass divided by gross liftoff mass (less payload)) for pressure-fed booster designs can be around 0.87; structurally lighter pump-fed vehicles normally have greater propellant fraction values that can be 0.92 or higher. For comparison, the propellant fractions for boosters with solid propulsion are typically around 0.90.

2.3 Hybrid Propulsion

It appears necessary to obtain some "optimal" solution to the dilemma of which is the best propulsion system. On the one hand, one has a high-thrust rocket engine with good performance but high complexity and cost, while on the other hand to get low complexity one must accept lower performance as well. It is at this point where hybrid rockets could become an attractive alternative.

Hybrid rockets combine elements from both types of rockets. In a hybrid rocket, a gaseous or liquid oxidizer is stored in a tank separate from a solid fuel grain. The fuel grain is placed inside a pressure chamber which lies between an oxidizer injector and the exit nozzle. The solid grain is hollowed out in the same fashion to produce a combustion port, very similar to that of a solid rocket motor type system. Unless the fuel is hypergolic (spontaneously combustible in the presence of an oxidizer), the fuel must be initially ignited in order to vaporize some of the fuel into a region just above the solid surface. Then, by injecting the oxidizer at a high mass flow rate and pressure into the pressure chamber/combustion port area, the oxidizer and fuel are free to react in a thin boundary layer just above the surface of the fuel grain. The high energy released and the high temperature attained both increase the energy in the flow and sustain the solid fuel vaporization. The combustion gases pass down the remainder of the combustion port and are expanded via nozzle. By changing the flow rate of the oxidizer, the total production of combustion gases and the energy going into them will be changed in a like fashion (increasing or decreasing). This fact demonstrates that hybrid rockets can be throttled. Given a simple ignition system that would efficiently initiate fuel burning prior to injecting the oxidizer, it also shows that hybrid rockets have start-stop-restart capabilities.

On the down side, the nature of the system renders itself to marginally higher combustion inefficiencies and also to variations in specific impulse. This has much to do with the (in)completeness of the mixing in the active combustion zone above the fuel surface. These effects are not so bad however; as far as specific impulse is concerned, hybrid rockets actually sit on the median between liquid and solid systems. Typical performance numbers are not difficult to find: for liquid systems, impulse can range from 3000 $N \cdot s/kg$ up to 4000 $N \cdot s/kg$; most solid systems operate at a specific impulse of 2000 to 2700 $N \cdot s/kg$. Performances generated thus far for experimental hybrid test engines lie in the range of 2750 to 3500 $N \cdot s/kg$. Moreover, it is not beyond possibility that further dedicated research and development of hybrid rocket motors will relieve some of the inefficiency problems and therefore boost the performance figures even higher. Another disadvantage to hybrids is that there will usually be unburned fuel slivers remaining after burning; however, this effect also plagues solid rockets. Clearly in many of these respects, the disadvantages of hybrid rockets are non-critical, and many are clearly not disadvantages with respect to solid systems.

Several advantages of hybrid systems are fairly simple to point out. The major benefit of solid rockets over hybrid rockets (and pump-fed liquid systems, too) is their simplicity. In hybrid systems, then, it seems that higher complexity is the price paid for better performance. However, note that the performance for these rockets is rival to that of liquid systems. Furthermore, note that hybrid rocket systems require support for only one fluid system, including tanks, valves, regulators, etc. In other words, although hybrid rockets are more complex than solid systems, they compare in performance to liquid systems while requiring only half of the "plumbing". This vastly reduces the overall systems weight and cost, while increasing its reliability (there will be fewer parts to fail). Hybrid rocket systems are also safer to produce and store, can be more ecologically safe with proper propellant choice, and the fuel grain, being inert, is stronger than manufactured solid propellant grains (for solid rockets), and is therefore more reliable. Finally the solid fuel grain of the hybrid gives it volumetric sizing advantages over the tankage required for liquid systems.

2.4 Airbreathing Propulsion

Traditionally rocket engines had been used for the primary propulsion of space vehicles. Certainly, above the atmosphere there is nothing that could reasonably replace rockets. However, in spite of their low thrust/weight ratio, limited Mach number range and high dynamic pressure trajectory, airbreathing engines offer a possible route forward with their intrinsically higher specific impulse.

As an airbreathing engine obtains its oxidizer from atmospheric air, it doesn't work in vacuum, where oxygen is absent. Hence an airbreathing engine can operate only in the aerial portion of the vehicle's trajectory, being necessary to employ rocket engines for larger altitudes.

The use of airbreathing propulsion for sounding rockets and launch vehicles can result in significant weight savings. This is due to the fact that oxygen from the atmosphere is utilized to reduce the amount of oxidizer that the vehicle must carry. The oxidizer weight savings then can be reinvested in a more robust vehicle structure and increased payload capacity (Whitlow, 2001). Notwithstanding this, airbreathing engines have a much lower thrust/weight ratio than rocket engines ($\approx 10\%$) which tends to offset the advantage of reduced fuel consumption.

Airbreathing engines come in a variety of forms. *Turboprops* and *turbofans* are highly efficient but are limited to subsonic speeds, which can be covered by mechanical accelerators which are more efficient. *Turbojets* are less efficient than turbofans at low speeds but are capable of about Mach 2. Afterburners have been used to exceed Mach 3, and Mach 5 *turbo-ramjets* have been proposed for commercial transports.

Ramjet Engines are conceptually the simplest of airbreathing engines, in that there are no rotating components. In the ramjet, air enters through a supersonic inlet where is it slowed and pressurized, then it is mixed with fuel and burned in the combustion chamber, then the gaseous products are expanded in the nozzle and exhausted from the vehicle at a speed exceeding that of the entering air. Ramjets typically operate in the flight Mach number range between 3 and 7, and are more often used for missile propulsion than for high speed aircraft propulsion. Extensive literature searche describes Mach 5.5 flight achieved and shows that ramjets can reach at least Mach 7, and possibly as high as Mach 11, over half the velocity needed for orbit. Ramjets have no thrust at zero velocity but exceed that of rockets above Mach 0.5 and exceed turbojets above about Mach 2.5. Ramjets have been flying for over 60 years, are simple, and have a number of advantageous traits.

Beyond Mach 5 (hypersonic domain), ramjet is less and less efficient. Increasing of air stagnation temperature and pressure tends to limit the performance and to increase the thermal and mechanical loads on the combustion chamber walls. To bypass these issues, the solution is to maintain the flow supersonic from the air inlet to the engine exit and to achieve the combustion in the supersonic flow. This is a *Scramjet Engine*. Scramjets are still at a NASA Technology Readiness Level of about 4 (out of 9). If they reach the necessary level of matureness, they could be used to improve on the already impressive ability of conventional ramjets.

Two of the leading concepts for airbreathing launch vehicles are the *rocket-based combined cycle* (RBCC) and *turbine-based combined cycle* (TBCC) propulsion systems. Combined cycle systems utilize several propulsion cycles integrated in a common flowpath. Typically, a scramjet and/or ramjet system is combined with a low speed accelerator. A rocket engine usually is included to propel the vehicle when the atmospheric oxygen levels become inadequate for airbreathing propulsion.

Whitlow (2001), Kuentzmann and Falempin (2002) and Varvill and Bond (2003) present excellent reviews of the characteristics of typical airbreathing engine types and the rationale for using airbreathing propulsion, including rocket-based and turbine-based combined cycles.

3.1 Propulsion System Applications

In simplistic terms, a propulsion system accelerates matter to provide a force of thrust that moves a vehicle or rotates it about its center of mass. The main functions[1] of different propulsion system are (Humble et al., 1995):

- **Launch** – accelerating a vehicle from Earth, or near Earth, through the atmosphere to a desired orbit;
- **Orbit insertion** – moving a vehicle from an initial orbit to a mission orbit;
- **Orbit maintenance and maneuvering** – keeping the space vehicle in the desired mission orbit or moving it to another desired orbit;
- **Attitude control** – providing torque to help keep a spacecraft pointed in the desired direction.

The first three functions — launch, orbit insertion, and orbit maintenance and maneuvering — provide the change in velocity (Δv) needed to translate the center of mass. The last function — attitude control — provides torque to rotate a vehicle about its center of mass (Humble et al., 1995).

Launch vehicles, in particular, need propulsion systems for only two basic functions: launch and control. The launching propulsion systems are of large thrust and large burn time. The control propulsion systems can have a low thrust and short burn time.

Different system types have traditionally applied to different missions. Table 2 summarizes the flight applications for cold-gas and chemical propulsion systems. The ranges of specific impulse indicated in this table corresponds to values of more usual systems.

A *cold-gas propulsion* system uses the-stored energy of a compressed gas to develop thrust. The gas, stored at high pressure, releases through a feed system and accelerates to a high velocity through a conventional converging/diverging nozzle. The advantages of this technology are that it is simple, safe to operate, and typically does not release contaminants into the space environment. The major disadvantage is that performance is quite low because stored pressure energy is usually far less than what is available from chemical reaction. For this reason, cold-gas systems apply mainly to attitude control and minor orbital maneuvers (Humble et al., 1995).

Airbreathing engines have intrinsically higher specific impulse than rocket engines. However they present a series of relative disadvantages: low thrust/weight ratio, limited Mach number range and high dynamic pressure trajectory. In addition, they can operate only in the aerial portion of the vehicle's trajectory, being necessary to employ rocket engines for larger altitudes.

Solid rocket motors are very common rocket-propulsion systems. They have several applications (Humble et al., 1995):

- Strap-on boosters for launch vehicles
- First-stage propulsion systems for launch vehicles
- Upper-stage propulsion systems for orbital-transfer vehicles
- Spin and despin systems for spacecraft
- Strategic and tactical missile-propulsion systems
- Gas generators for starting liquid engines and pressuring tanks.

[1] Other applications as, for example, a gas generator, are not strictly propulsion systems.

Table 2: Applications for Chemical Propulsion and Cold-Gas Engines.

System Type	Applications					Typical I_{sp} (N · s/kg)
	Launch	Orbit Insertion		Orbit Maint. & Maneuver	Attitude Control	
		Apogee	Perigee			
Cold gas				x	x	500 – 750
Airbreathing	x					30000 – 40000
Solid	x	x	x			2600 – 3000
Hybrid	x	x	x	x		2900 – 3500
Pump-fed bipropellant	x	x	x			2800 – 4300
Pressure-fed bipropellant	x	x	x	x	x	2600 – 3800
Dual-mode mono/biprop.	x	x	x	x	x	1400 – 3600
Monopropellant		x	x	x	x	1400 – 2250
Electr. heated monoprop.				x		3000 – 15000

Hybrid propulsion could be applied to boosters and upper stages, orbital maneuvering and orbital transfer systems. However, due to the impossibility of fine tuning of the thrust throttling, it can not be used for attitude control.

Table 2 shows that some form of liquid propulsion applies to any phase of space flight. Applications requiring large impulses (ascent, orbital transfer, and upper stages) typically use higher-performance (specific impulse) propellants with a pump-feed system to reduce the propellant tank's mass and reduce engine size. Pressure-fed systems for launch vehicles usually apply to upper stages and to auxiliary propulsion systems. Lower-impulse applications, such as perigee or apogee kick motors and orbit-adjust systems, may or may not use pumps. The choice typically depends upon whether one can lower system mass, lower the parts count, or lower the cost. For applications needing even smaller impulse (stationkeeping and attitude control), system simplicity takes precedence over specific-impulse performance: it is used tank pressure to feed low-specific-impulse propellants, such as monopropellant hydrazine, into the thruster. The dual-mode operation (mono- or bipropellant) enables wide thrust variability and flexibility for different applications (Oliveira, 2000b). Electrically heated systems use electric heating to increase the propellant's exhaust velocity and thereby the specific impulse. These systems have relatively low thrust and typically apply to orbit-maintenance applications.

3.2 Rocket Propellants

The type of propellants used in designing a new launch vehicle is a key factor in the resulting development, manufacturing, and operating costs. Traditionally space launch systems have used either liquid or solid propulsion systems or some combination of the two. Lately, hybrid propellant concepts have matured sufficiently to be considered as a valid propellant alternative. A hybrid propellant combination typically consists of a solid and a liquid constituent — in most cases, a solid fuel and a liquid oxidizer. Table 3 lists some specifics of the various trades between solids, liquids, and hybrids (Andrews and Haberman, 1991; Cook et al., 1992; McDonald, 1992).

Each of the three basic families of rocket propellants offers a large set of unique characteristics, as shown in Tab. 3, for the launch vehicle designer. Certainly, in terms of performance, one optimal propellant exists for each specific application of the propulsion system. Likewise, in a multi-stage launch vehicle, there is one optimal chemical system for each stage, not necessarily the same for all stages. Traditionally, the choice is governed by the payload, length of flight, burnout velocity and also by the kinetic and utilization qualities of the propellant. But it is not all. In addition to a reduced global cost, it is desirable to reduce the number of different fluids and the number of different propulsion systems in a same vehicle. This could be done using the same propellant combinations and similar propulsion systems in the first- and upper-stages (and possibly in auxiliary systems). Therefore, the proper choice of propellant could reduce the

Table 3: Propellant Selection Trades.

	Solids	**Liquids**	**Hybrids**
Impulse density	High	Moderate to low	Moderate
Storability	Good	Limited[a]	Good[b]
Development risk	Moderate	High[c]	Very high[d]
Development cost	High	Highest[c]	Higher[d]
Design complexity	Low to moderate	Very high[c]	Moderate
Testability	None[e]	Good	Limited[e]
Inspectability	Poor	Good	Good for oxidizer tank, poor for fuel[f]
Reliability	Very high	High[g]	Probably very high[h]
Dependability	Very high	Moderate[i]	Probably high[h]
Safety concerns	Significant from factory to launch	Significant after loading on pad	Insignificant
Environmental considerations	Ozone depletion, CO_2 increase, acid rain	Ozone depletion, CO_2 increase[j]	Ozone depletion, CO_2 increase[j]
Throttleability	Predetermined thrust profile only	Good	Good
Thrust termination	Difficult	Simple	Simple
Payload environment	Relatively harsh	Relatively benign	Relatively benign
Ground handling considerations	Difficult	Moderate	Moderate to difficult
Weather considerations	Narrow range of operating temperatures, susceptible to corrosion[k]	Wide range of operating temperatures, most susceptible to inflight wind transients	Narrow range of operating temperatures, susceptible to corrosion[k]
Propellant cost	High	Moderate[l]	Moderate
Manufacturing cost	Low	High[m]	Probably moderate[h]
Engine-out applicability	Impractical	Good if vehicle properly designed	Impractical
Reusability applicability	Very poor	Good	Poor
Propellant aging concerns	Significant	None	Minimal

[a] Assumes cryogenic liquids. Hypergolics have good storability, but are highly toxic and environmentally unfriendly. [b] Only for solid component of the propellant combination. [c] Only for pump-fed propulsion systems; moderate for pressure-fed systems. [d] Due to hybrid technology and cost model immaturity. [e] For actual flight system components. [f] Poor inspectability of fuel not as much of a concern due to the hybrid system's relative insensitivity to grain defects. [g] Only for pump-fed propulsion systems; very high for pressure-fed systems. [h] Projected. [i] Dependability increases with increasing system simplicity. [j] Assumes nontoxic hypergolics. [k] Especially for solid booster segment field joints. [l] Assumes LOX/hydrogen. LOX/RP-1 is low; hypergolics are rated high. [m] Only for pump-fed propulsion systems; low to moderate for pressure-fed systems.

complexity and the cost of development and operation of a launch vehicle (Oliveira, 2000b).

3.3 Propulsion System Selection

3.3.1 The 4-Level Model

Space activity is a complex business conducted in the most severe of environments (technically and politically). It is a problem of integration at many levels. Success requires the understanding of how a part of the space "business" interacts with all of the other parts. Particularly, the choice of a propulsion system for a launch vehicle involves decisions at the four hierarchic levels shown in the Fig. 2.

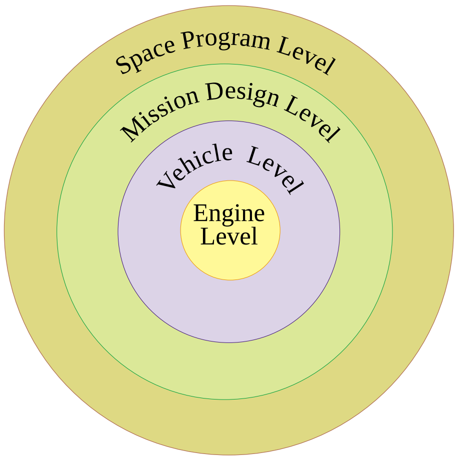

Figure 2: Propulsion Systems within a 4-Level Model of Space Systems.

The selection of an 'optimum' propulsion system involves an assessment of a number of interdependent factors such: 1) engine performance, 2) engine/airframe integration, 3) technology level, 4) development cost, and 5) recurrent costs. The relative importance of these factors depends on the severity of the mission and the vehicle characteristics, and on the global directions of the space program. Therefore the selective process must satisfies requirements in different levels, as discussed above.

In view of previous arguments, it become clear that the propulsion problem must be discussed in its proper context. The correct form of making the judgment is, therefore, to analyze the question inside of this 4-level model, or maybe in a even higher level, taking into account the sectorial politics and the great national objectives. This way, it is necessary to know the stated directions and the activities of the Brazilian Space Program in order to better approach the theme.

3.3.2 The Brazilian Space Program

The current *National Space Activities Program* (PNAE), as it is known the Brazilian Space Program, covers a 10 year period from 1998 to 2007 (AEB, 1998). It consists of eight major initiatives: Space Applications, Satellites and Payloads, Satellite Launching Vehicles and Sounding Rockets, Space Infrastructure, Space Sciences, R&D on Space Technologies, Training and Development of Human Resources and Support to the Qualification of the National Space Industry.

The National Institute for Space Research (INPE), under the aegis of the Ministry of Science and Technology, is responsible for satellite development and related technologies, and pursuing R&D in the field of space applications, Earth observation and space and atmospheric sciences.

The INPE's Propulsion team has a good experience on design and production of monopropellant hydrazine engines in the thrust range 2–115 N. The smaller engines are used for attitude and orbit control of satellites developed by INPE; the 115 N hydrazine engine was designed to be used for roll control of VLS-1 launcher. New hydrazine catalyst-beds were also developed. More recently, the INPE's Propulsion Team is focusing on the development of small (150–200 N) bipropellant engines to be used as satellite apogee-engines.

The other objective of PNAE is to give the country the capability to design, develop, and build launch vehicles for suborbital payloads and satellites. It includes three sub-programs: sounding rockets, launch vehicles for small satellites, and launch vehicles for medium satellites. The Institute of Aeronautics and Space (IAE), under the Ministry of Defense, is responsible for the execution of these three sub-programs.

Since the early 1970's IAE has been engaged a long-term launcher development program that started with the development of a successful family of sounding rockets named SONDA. The sounding rocket sub-program continues and is now benefiting from technologies developed for the satellite launcher sub-program. The first and second flights of the VLS-1 launcher (in 1997 and 1999 respectively) both failed. A third tentative was planned to occur in August 24, 2003, but two days before it was frustrated by an catastrophic accident that destructed the vehicle at launch pad. A smaller launcher, VLM, is also planned for the near future as an alternative for launching micro-satellites. All these vehicles were based on solid propulsion. The next launcher in the program could be the VLS-2, which is planned to have an enlarged capacity over previous Brazilian launch vehicles, by using or not liquid propulsion stages.

This way, IAE started its space activities using solid propulsion, having gathered certain experience in this type of propulsion. This competence in solid propulsion brought many technological advances for the Brazilian industry, mainly for the military sector. Unfortunately, this conquest came followed by many international barriers and restrictions, attributed to the distrust in the true intentions of the Brazilian Space Program. These obstacles had increased the difficulties for the development of both military and non-military vehicles. It must be remembered, however, that most of them could have been mitigated and maybe completely revoked with use of diplomacy and able interlocutors. By the way, the incapacity of the Brazilian administrators of the space sector in negotiating and well representing the sectorial interests was always notable.

Now, after many years after beginning the development of the space program, it can be said that the initial option for the solid propulsion can not have been the best choice. Pressure-fed systems would have been simpler and cheaper alternatives, with shorter development cycles. Liquid propellants available in the country could have been used for, not being necessary to develop the technology of solid propellant production, nor to construct plants for production and processing of such propellants.

However, it must be understood the historical and strategic reasons that had culminated with the option for solid propulsion. The dual-use character — in this in case, the possibility of military application — certainly was decisive.

Moreover, must be considered that this fact was the result of more a contingency than an exclusionist option, since the use of liquid propulsion was always in the IAE plans. In the meantime, facing the limitation of technical and financial resources, and an administrative incapacity, it is easy to understand why the liquid alternative has never been carried out.

3.4 Selection Criteria

Which is the best chemical propulsion system for an aerospace vehicle? Certainly there is no absolute answer to this question, since, besides its dependence on the particular application of the vehicle itself, it will also depend on the technical, technological, economical and time availabilities. Moreover, it still depends on how this particular vehicle is included in the context of the space program to which it belongs, and on which would be the directions to be followed inside this program.

The basic criteria for the selection of propulsion systems is to meet the PNAE goals in shorter time and lower costs. Additionally, the chosen system must be low-cost, affordable, technically feasible, safe, reliable, and environmentally clean.

It is in light of these criteria and of the previously presented overview of chemical propulsion that a discussion has been established in order to tentatively answer what type of propulsion is better for the Brazilian rockets.

3.5 Analysis of Propulsion Candidates

The following analysis considers two points of view: the first begins from the *availabilities* of technical alternatives, and the second begins from the *necessities* for accomplishing the PNAE goals.

3.5.1 First Point of View – Analysis of Availabilities

The candidate engines can be split into two broad groups, namely pure rockets and engines with an airbreathing component. Each alternative within these groups will be analyzed next.

Since none of the airbreathers are capable of accelerating a launch vehicle all the way to orbital velocity, a practical vehicle will always have an onboard rocket engine to complete the ascent. Therefore the use of airbreathing has always been proposed within the context of improving the specific impulse of pure rocket propulsion during the initial lower Mach portion of the trajectory. So, for sounding rockets or launch vehicles, the airbreathing propulsion must always be combined with some type of rocket-propulsion. Although potentially attractive, the integration of the airbreathing options with airframe and other propulsion types still need larger technological matureness, not adjusting to today PNAE bolder pretensions.

The capacity in solid propulsion in IAE reached a good level. It had permitted the development of technologies to produce solid propellants, of technologies for production of metallic and composite motor cases, of production of ablative nozzles, the development of a system of secondary injection, etc. Most of these advances could be useful in developing liquid and hybrid propulsion systems.

Even though some people try to convince the general community, a solid propulsion is not outdated and nor worse than other types of chemical propulsion systems. If this were true, how could be explained the renewed interest of foreign companies and governmental agencies in this subject (Moore, 2003)? It must be still remembered that some new launch vehicle projects in Europe and in U.S.A. are based on solid propulsion (e.g., Vega and Taurus launch vehicles).

The technology of hybrid propulsion is enough mature for use in many countries. Nevertheless, even with a certain qualification in solid propulsion, which certainly could contribute for an incursion in this another modality of propulsion, for application here in Brazil would be necessary to advance first in the domain of liquid propulsion. It is concluded from here that still it is not the moment to invest in hybrid propulsion, except at the academic circles.

As seen above, the qualification in the solid propulsion must be continued or, at least, be kept in the current levels. On the other hand, one it is not recommended to invest intensively in hybrid and airbreathing propulsions, since one would incur into the error to burn important stages. It now remains to be analyzed the viability of the liquid propulsion.

The liquid pump-fed systems are in general very complex and costly. Their development demands technical and technological bases not available presently at IAE. The possibilities to develop staged-combustion or other closed cycles are minima. However, systems with gas generator cycle are considerably simpler and could become feasible at long-term. It is necessary still to remember that the development of a pump-fed LRE is made initially by using a pressure-fed version of such LRE.

In the other side, liquid pressure-fed systems seems to be very interesting within the PNAE context. A pressure-fed liquid propulsion system is an extremely versatile design concept, which could be employed in both auxiliary and main propulsion systems. Such design can be as simple as a solid motor for applications requiring a single programmed impulse, as in the case of a first-stage of a launch vehicle. It can also be designed for throttling, stop and restart capability required for the most sophisticated aerospace missions (Oliveira, 2000b).

Pressure-fed propulsion systems are always cheaper and quicker to develop than the pump-fed variety. In comparison with solid propulsion systems, they could present equivalent simplicity but have many advantages. Overall, one should expect newly designed pressure-fed liquid rockets to have roughly the same propellant fraction as has been available with solids for many years, to have a higher specific impulse, to have more environmentally friendly exhaust products of propellant combustion and to have a wide controllability (Oliveira, 2000a). Additionally, nontoxic, storable liquid propellant combinations cost at least ten times less than their solid counterparts (Oliveira, 2000c).

3.5.2 Second Point of View – Analysis of Necessities

Looking at the goals of the Brazilian Space Program one can argue: it would be possible to fulfill them only with solid propulsion? Yes! There is not doubt that even a launch vehicle with medium capacity could be constructed with SRM's in all vehicle stages. Obviously the attitude control could be made with small pressure-fed engines (mono- or bipropellant, developed at INPE or maybe at IAE) or even though with cold-gas engines.

Then, another question appears: It would be interesting to compose this vehicle with liquid propulsion systems? Well, this question is a little more complex, and the answer now is not so simple. A tentative answer will be outlined in the next paragraphs.

At first, in terms of reliability, it is interesting to reduce the number of components and interfaces. In this way, the ideal number of stages of the vehicle is two or, at maximum, three. In case of a two-stage vehicle it would probably be necessary to make re-ignition of the second stage, which could only be carried out by using LRE (or HRE). In a three-stage version, it is not excluded the use of solid propellant for the two upper-stages. Therefore, only for a TSTO it will be necessary to use a LRE (or maybe a HRE).

Moreover, it must be considered that it is more advantageous to use high-performance systems in the upper-stages than in the first stage of a multi-stage vehicle. This way, a SRM, a HRE or a low-performance LRE (for example, a pressure-fed LRE) could be used in the first-stage and/or booster. Other alternative for the first-stage is an airbreathing engine. Although conceptually interesting, this alternative hardly could be carried over in the given context, as previously discussed.

In conclusion, it seems to be the right time to initiate the research and development of liquid propulsion systems. Although it is not indispensable, the use of pressure-fed liquid propulsion can permit to develop vehicles with higher precision for orbit insertion, lower cost and more friendly to the environment. Additionally, it could propitiate the necessary capacity for using hybrid propulsion and liquid pump-fed systems, if it will be decided so.

For a consistent capacitation, the learning process should be gradual and obey its proper intrinsic hierarchy. The suggested sequence of development is the following:

1. monopropellant gas-generators (HTP, HAN, Hidrazine, Ammonia).
2. monopropellant Reaction control Systems (RCS's)
3. bipropellant gas-generators

4. bipropellant RCS's
5. dual-mode bipropellant RCS's
6. pressure-fed upper-stages
7. pressure-fed first-stages/boosters

These sequence must follow directions set by a global program: one or more families of vehicles (sounding rockets and launchers), where flexibility and modularity are accounted for.

The structure and attributions set in PNAE must be reviewed in order to better adjust to its goals. For example, it is desirable that INPE and IAE work together in the liquid propulsion field, since INPE has already a large experience on the subject, which could be useful to IAE.

4 CONCLUSIONS

By means of a design review of the relevant characteristics of both rocket and airbreathing engines, together with an analysis of historical facts about the space development in Brazil, this study sets out the rationale for the selection of chemical propulsion systems for the main and auxiliary propulsion system of Brazilian sounding rockets and launchers. It was shown that the selection involves decisions in at least four hierarchic levels within the PNAE (program architecture → mission → vehicle → propulsion systems).

The objectives of PNAE, in terms of space vectors, are to develop sounding rockets and launch vehicles with micro and small launch capacities. Although these goals could be meet with solid propulsion, it seems to be the opportune time to invest in liquid propulsion systems. The suggested approach is to develop low-cost vehicles using very limited technical capacity and technology available in Brazil, looking for taking advantage of previous experience in solid rocket propulsion, and maximizing the use of the existing ground installations for test and launching, in a gradual process.

The propulsion systems types and the propellant combinations to be used must be judiciously selected since they define the complexity, reliability, cost, and feasibility of the entire vehicle.

It was recommended to develop pressure-fed liquid systems due to simplicity, low-cost and extremely versatile design concept, which could take advantage of the existing competency and facilities.

The type and mixture ratio of the propellant components determine the shapes and relative positions of tanks, the pressurization and the cooling systems, and 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. Storable, and non-toxic propellants, with large availability in the national territory, are the most indicated.

Finally, considering the space effort as a commercial and strategic necessity, as well as a matter of national prestige, the Alcântara catastrophe provided vivid warning: it is necessary to redefine all the PNAE with respect to the space vectors, establishing the proper pacing and control, and providing the necessary resources. In addition, a disturbing "Space Design Law" (Akin, 1998) and its corollary could never be forgotten:

Akin's Law No. 34: Space is a completely unforgiving environment. If you screw up the engineering, somebody dies (and there's no partial credit because most of the analysis was right. . .)

Connolly's Corollary: Space systems are designed in a completely unforgiving environment. If you screw up the engineering, millions of dollars of equipment is lost, and people are fired.

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