CHAPTER 14

Future of Solid Rocket Propulsion

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1. Increase of Solid Propellant Energy

The progress made in the energetic characteristics of solid propellants during the 1950s and the 1960s was followed by a period of disillusionment.

As with all new technology, the initial progress had been very rapid. It resulted from an excellent synergy between the needs related to applications and the emergence on the market of chemicals supplied by the chemical industry, well suited for the formulation of binders for solid propellants: PVC, polyurethane, followed by more specific products such as various kinds of liquid functional polybutadienes. This led to the creation of today's typical composite propellant, associating a polybutadiene binder with excellent mechanical characteristics in a very wide range of temperatures to a high content of oxidizers and fuels: ammonium perchlorate and aluminum respectively. This is a particularly stable system, and involves a reasonably easy production process in facilities where, aside from a few specific production phases, the only hazard of concern is that of fire. Consequently, this type of composition has progressively spread to a great number of applications, such as missiles, rockets, and gas generators. For these applications the immediate availability, long service life and good performance represent major advantages, at least where the dimensions of the motor are not too limited by space constraints, such as in the case of strategic missiles on submarines, portable ground-air systems, or integral boosters on ramjets.

The research work done during the 1960s encountered great difficulties in the synthesis and production of new molecules designed to increase the energy of these propellants.

A great number of oxidizers more powerful and denser than ammonium perchlorate were synthesized, tested and abandoned because of a high chemical reactivity or a lack of stability (NO_2ClO_4, for example) made them incompatible with the existing binders, or because of high sensitivity to shock or friction for industrial production (hydrazine mono or diperchlorate, for example).

Techniques were subsequently developed to improve the compatibility of energetic solid oxidizers included in the propellant: surface modifications and, in particular, encapsulation of the particles by organic polymers insoluble in the binder and compatible with the rest of the composition. These techniques resulted in a decrease of the energy gain expected from the formulation, and a significant cost increase for the preparation of the propellant, but they may conceivably be used again in the future.

Many failures were also experienced with metallic fuels. Metallic hydrides either exhibited densities that were too low to be interesting when the hydrides were stable (LiH, $LiAlH_4$), or they were not stable unless complexed with an organic molecule, thereby losing a good deal of their advantage (AlH_3, BeH_2). Extensive research has been done during the 1960s, in the United States as well as in France and probably in the USSR, on composite propellants containing beryllium. The reason for this is that the addition of this metal significantly increases the specific impulse, without creating any problems of compatibility with the hydrocarbon binders or ammonium perchlorate. These developments were virtually abandoned because of the very high toxicity of beryllium and particularly of its oxide resulting from combustion, although there are controversies concerning the real toxicity of oxide formed at the very high temperature of combustion in the motor. This approach appears closed for the moment, although the possibility of starting the research again comes up periodically, particularly for space applications. There is one metal, however, that could have a definite future in some applications, and in particular for tactical missiles of smaller sizes, such as ramjet boosters. This is zirconium, with its very high density (6.49), resulting in propellant with a volumetric specific impulse clearly above that of the conventional polybutadiene–AP–Al propellant.

The thermochemistry and energetics of these various compositions are particularly well described in the work from Boisson [1] which, although not recent, continues to be recommended as a reference.

In the end, there seem to be two approaches open for the future: one is the use of nitrated or nitro derivatives; the other, in the distant future, may be the use of molecules containing fluorine not highly chemically bound in radicals of the NF_2 type.

Among today's most widely used energetic compounds, special attention has been given to HMX which, in spite of its highly explosive nature, exhibits high density, energy and stability. Two applications are: (1) the development of specific polybutadiene–AP–Al formulations with some percentages of HMX (12-20%); (2) XLDB type of formulation whose energetic binder, more highly oxygenated, provides a higher specific impulse due to a possible high content of HMX. These two types of compositions are being applied either in apogee motors for space launchers (American PAM D_2, for example), or in advanced ballistic missiles for space launchers: Trident 1 C4, Trident 2 D5, the third stage of the MX, and Midgetman in the United States.

Research continues in many countries on energetic solids or binders, or on nitrated plasticizers that are more energetic or stable than binders with a very high content of nitroglycerine. Molecules such as hexanitrohexa aza adamantane or wurtzitane are the object of intensive research.

The avenue of the difluoraminated-type binders and oxidizers, which was pursued because of the potential of very high specific impulse and density, continues to be a highly difficult area of research direction. It seems to be particularly oriented toward gem-difluoraminate molecules which preferably include the geminal $C(NF_2)_2$ rather than the vicinal $CHNF_2$, which is unstable. This chemistry, which uses the difluoramine NF_2H as a starting material, is a difficult chemistry and it is very expensive.

However, an outside candidate has emerged that leads us to believe that in the very near future we will be able to increase the energetic levels of today's propellants. It has been discovered in the United States that aliphatic molecules containing the azide entity, N_3, are stable and not very sensitive to shock or friction. One particular polymer is presently under development, the glycidyl azide polymer (GAP) [2].

Table 1 summarizes the main chemical features that are involved in the research on new energetic compounds with high heat of formation and high heat of combustion.

In the end there seems to be a definite trend again toward the research of higher energies, which will be discussed in the next section. This has occurred after a period during which research budgets for the improvement of thermodynamic characteristics were drastically cut because of the disappointments encountered in the chemistry of high energy materials. These disappointments result in a great diversification of the more conventional compositions in terms of their applications, which we will also discuss later.

TABLE 1 *High energy groups*

Group	ΔHf (kcal/mole)	Use
$-C-O-NO_2$	−19.4	plasticizers
$-C-NO_2$	−15.8	solids polymers plasticizers
$-N-NO_2$	17.8	solids plasticizers
$-C-N_3$	80	plasticizers polymers
$-C-NF_2$	−7.8	solids plasticizers polymers

2. Propulsion of Strategic Missiles

The search for optimal propellant performance — specific impulse I_s and volumetric specific impulse $I_s.\rho$ — will continue to be the most important research mission, coupled with other expected technological progress which will improve the propellant mass fraction (composite cases with very high specific resistance, nozzle materials, and thermal protection) and with the miniaturization of the nuclear warheads. These energetic gains will provide the flexibility of design and usage corresponding to the various constraints of the missions. It will involve, for example:

- For a missile of a given size (missiles on board submarines), increasing the range or the number of warheads, countermeasures (decoys), or the number of potential targets.
- A miniaturization of strategic missiles (the Midgetman concept in the United States, project SX in France) to facilitate their transport and their utilization, while at the same time deceasing their cost, allowing a corresponding increase in the number of missiles.
- The evolution of past performances and those possible in the future is illustrated in Table 2, which shows the improvement in performance of propellants (in terms of the volumetric impulse I_s) over the years, based on the American missiles until 1984, and then extrapolating from today's state of the art (propellants existing but not yet manufactured industrially). The source for this table is a paper written by D. Quentin [3], to which we will refer to a number of times in the following sections.

TABLE 2 *Past and predicted evolution of solid propellants for strategic missiles*

Formulation	Theoretical I_s standard conditions	ρ g/cm^3	$I_s.\rho$	Estimated date of completion of industrial development
Butalane 68/20	265	1.815	481	1968
Nitralane Trident C4	271	1.84	498	1973
Nitralane Trident C5	273	1.87	510	1978
F1	276	1.89	522	1985
F2	280	1.91	535	1995
F3	296	1.91	565	2010

Note: The performances assigned to the future formulations (F1, F2 and F3) are the results of calculations, and consequently involve a certain amount of uncertainty concerning the possibility of attaining them in practice.
The dates correspond to the demonstration of the industrial feasibility of the propellants rather than their introduction in a missile program.
F1 and F2 compositions are based on nitrated or azide ingredients.
F3 composition contains difluoraminated derivatives.

Based on these elements, we see that, taking only thermodynamics into account, there is a considerable potential for improvement.

However, we should point out that these propellants, in comparison with the conventional composite propellants, present the same drawbacks as those experienced with high-energy XLDB propellants: (1) small critical diameter; (2) manufacturing involving delicate phases because of the use of large amounts of explosive ingredients. Solving the latter requires high investments, and thorough knowledge and control of the deflagration–detonation transition phenomenon. The approach taken in the United States with the ballistic missiles of the Trident and MX family shows, however, that these various aspects can be handled, resulting in reliable, high-performance systems.

Before they can be produced, these future propellants will also need to have sufficient mechanical properties allowing them to be case-bonded, and aging properties that are compatible with the typical service life of the ballistic missiles motors, i.e. at least 10 years.

The architecture of the grains, based on the levels attained today (loading ratio greater than 95%), should not evolve noticeably if the architecture of the motor remains the same (we will discuss the concept of integrated stages further).

Another general possible evolution is related to the hardening of the main stages of the missiles against space-based lasers that could be used in the SDI concept. This hardening could involve rotation of the missile and much lower burn times of the stages, phases during which it is the most sensitive. So high-rate, high-energy propellants would be considered.

Special propulsion systems need to be contemplated for the post-boost control systems which require special solid propellants. The best propellant energy management in these systems implies the availability of solid propellant with modulable flow rates or the availability of extinguishable and re-ignitable (start-stop) systems.

The future trends seem to be as follows: for ground-based missiles with a large number of warheads to deliver we are experiencing a return to liquid propellants systems. This is due to the fact that they allow a greater amount of flexibility in adjusting the thrust, and easy control of the extinction and re-ignition of the motor, with very high specific impulses.

In the case of systems on board submarines, the liquid propellants are less acceptable (risks of leaks from the tanks, corrosion, limited space available, and low density of the propellants). Two types of systems are possible for present and next future systems. The classical post boost system used on missiles of the Poseidon and Trident family, which uses propellant gases produced by a generator modulated by a valve. At the technical level this implies the availability of the propellant with low burning rates (the operational times must last several minutes) and the highest possible specific impulse, while not exceeding gas temperatures acceptable for the valves and the pipes of the system. In the United States the materials used are generally Colombium alloys, which limit the temperatures to approximately 1900 K. In France extensive work is being done with carbon-carbon composite materials allowing temperatures up to 2400–2500 K, and consequently, higher specific impulses. Butamites or nitramites, with "cold" nitrated binder and high HMX content, are propellants well suited for this type of need. Another characteristic of these types of systems is the need for very clean combustion gases, to avoid clogging of valves and pipes. Mineral compounds are generally not used in the composition of the propellant; as for inhibitors and the thermal protection of the chamber, gasifiable formulations, also used in low-signature tactical missiles, are preferable.

With the throttlable or controllable system, with separate solid propellants, the main motor functions only when a gas generator — with low combustion rate — generates flows inside the combustion chamber. When the gas injection is interrupted the main grain extinguishes. The corresponding propellant compositions are often fairly reducing for the generator, and oxygenated for the main grain. High specific impulses, associated with an operation that includes more than ten thrust pulses separated by motor extinction phases of varying duration, have been demonstrated in France.

A concept studied by Aerojet [4] is similar to this system. It features two solid propellant generators: one for oxidizing gases and the other for the reducing gases. Their flow rates are independently adjustable; they both flow into one single combustion chamber.

We should also mention that in the area of general architecture for multistage ballistic missiles, an interest is developing in an integrated stage concept, whereby the front end of the lower stage forms the exit cone for the nozzle of the next higher stage. This concept would lead to a 20% increase in range. A "forced deflection" nozzle, using a special boron-based propellant, has been demonstrated in the United States in a chamber simulating high-altitude conditions [5]. A related system, though less ambitious in terms of the innovations involved, has been recently demonstrated [6].

Finally, we should also note, in relation to the development of solid propellant boosters for space launchers, the trend of manufacturing facilities toward the processing of very large quantities of composite propellants in one manufacturing operation, still using the batch process. The unit operation has grown from 2–3 tons to approximately 15 tons. Today, modern automation technology results indicate significant drops in manufacturing costs.

For the longer-term continuous processes, presenting revolutionary possibilities are being developed and will be addressed in the section on space boosters.

3. Propellants for Tactical Missiles

Each mission has its own specifications and requirements, as illustrated in Table 3. Although this presentation is largely arbitrary — for instance no

TABLE 3 *Characteristics of solid propellants for tactical missiles as a function of their missions*

Types of Missiles	$I_s\rho$	Signature	Temperature coefficient	Duration of combustion
Artillery rockets	×		× ×	
Anti-tank				
Rockets		× × ×	× ×	very short
SR	×	× × ×	× ×	
M and LR	× ×	× × ×	× ×	
Ground air				
VSR	×		× ×	
MR	× ×	× ×	× ×	long
LR	× ×	× ×	× ×	
Air-ground				
Rockets	×	×	× ×	long*
Missiles	× ×	×	× ×	
Air-air				
SR	× ×	×	× ×	
MR	× ×	×	× ×	
Sea-sea	× ×	× × ×	×	long*

Note: ×, not an important criterion; × ×, of average importance; × × ×, highly important. SR = short range; MR = medium range; LR = long range; VSR = very short range.

missile manufacturer believes that the cost of the propellant is marginally important — it still allows us to identify the trends. Naturally, the service life and storage and operational safety are also included in the main specifications.

Before getting to the solutions (propellants, grain geometry) for these problems, it would be interesting to take a closer look at the evolution of some specifications.

3.1. EVOLUTION OF THE NEED

3.1.1. Signature and penetration

The lowering of the electromagnetic, infrared, and optical signatures of missiles is intended above all to delay the use of countermeasures. In fact, a low signature is one of the means of ensuring the superiority of the attack over defense, so that future missiles will retain their capability of penetration.

Extensive efforts are devoted to reducing the visible, infrared, and electromagnetic signatures. A reduction of the electromagnetic signature — characterized by the radar cross-section — is obtained mostly by changing the architecture or the materials: limiting "bright spots", using coatings that absorb or diffuse radar waves and special shapes, which could lead to missiles with elliptical or triangular sections. This in turn would result in completely new problems in terms of the propellant grain.

We will not discuss decoy systems, although we will comment briefly on the maneuvering capability the manufacturers would like to provide their missiles in order to outwit the defense systems. In terms of propulsion, such a capability would imply several indispensable attributes, including: (1) the modulation of the thrust which may lead, even for a missile, to three or even four successive thrust levels which, of course, becomes extremely problematic for a single grain; (2) the capability of the grain to withstand acceleration factors.

3.1.2. *Environment*

The number and severity of constraints under which future missiles will be used are continually increasing, particularly in terms of the extreme temperatures of operation and storage. In the course of the last 30 years these have progressed from propellants usable in a −30°C to +50°C temperature range to propellants with a working range from −54°C to +70°C, and able to resist to peaks reaching temperatures close to 100°C. This corresponds, in particular, to the extension of the flight domains (altitude and speed) of aircraft, for air-launched missiles.

These constraints present the grain designers with two critical problems. Not only is it necessary to maintain the mechanical and physical integrity of the grain within the operational ranges, and its reliability after severe thermal cycles — consequently requiring excellent mechanical properties at all temperatures — but it is also necessary to maintain the performance (thrust, pressure versus time) in the same range (reduction of temperature coefficient).

The problems linked to the temperature ranges involve several other parameters, including:

- the intrinsic mechanical properties of the propellant;
- the geometry of the grain;
- the grain-case interaction, related to deformation under pressure from the case and to its thermal expansion characteristics.

This last point is an important one. Indeed, the evolution toward increasingly thinner metallic cases, made feasible by flow-turning processes and the use of filament-wound cases (Kevlar and carbon fibers), modifies considerably the behavior of the motors in terms of deformations under pressure (to which are added the difficulties of calculation and local anisotropies). It also modifies the need to take into account the whole composite propellant-case to calculate the stresses and strains which determine the safety coefficient and the service life of the motor.

Naturally, the improvement of the mechanical characteristics of the propellant give the grain designer a greater amount of flexibility in his search

for a solution. In addition, the generalization of the three-dimensional analyses validated through experiments, and the use of more sophisticated rheological models, improve the reliability of the predictions and the estimation of the service life.

3.1.3. *Maneuverability; thrust modulation*

We mentioned, when discussing the signature, the necessity for maneuverability on part or all of the trajectory to defend against anti-missile weapons. Without a doubt the next generation of air-sea or sea-sea missiles will feature a supersonic final path to foil the enemy defenses. Conversely, anti-missile missiles design will have to be able to react almost instantly, to maneuver with agility once the target has been detected.

3.1.4. *Increase range*

For air-ground, air-sea, and sea-sea missiles the possibilities of detection or identification of remote targets and the desire to escape from enemy defenses (such as launching aircraft or battleship) requires significant increases in missiles range, which, as we will discuss later, demonstrates the value of the air-breathing type of solutions.

3.1.5. *Vulnerability*

Low vulnerability specifications of the type described in Chapter 8 will certainly be imposed for all missiles. In the United States the objective, a very ambitious one, is to use missiles meeting "insensitive munition" requirements by 1998.

3.2. EVOLUTION OF THE TACTICAL PROPULSION

3.2.1. *Propellants*

Propellants are generally classified into three families:

- double-base (extruded or cast);
- composite with inert binder;
- composite modified double-base with energetic binders, CMDB or XLDB type.

The first two families — also the oldest — will continue to develop in two major directions: increase of burning rate ranges, and development of low-cost processes for industrial production.

The third family will be affected by the application of high-energy, low-signature propellants and their development within the framework of low vulnerability specifications.

The expected improvement, over the years, of the performance of the low-signature propellants for tactical missiles ($I_s\rho$) is illustrated in Table 4.

One of the major difficulties encountered with the newer types of smokeless high-energy propellants is the present limitations in rates of combustion available. This is certainly one of the main subjects for research in the near future.

3.2.2. *Grains for thrust modulations*

There are already many grains that have two thrust rates and thrust ratios capable of reaching factors of 7 to 8. These rates, however, are currently predetermined, while the missile designers wish to be able to trigger an "overrate" on request, as a function of the proximity of the target. Designs with complex geometries — with an increase of the burning surface at the desired moment — are being developed and are expected to be operational within the next few years, particularly for applications on the new sea-sea, air-surface, or air-air missiles [7,8].

3.2.3. *Increase range: air-breathing systems*

With air-ground and sea-sea missiles, and sometimes also ground-air, the ranges are limited by the weight of the missile, and also by the burn time available for the sustainer grains (more than 150 s is now available).

A simple solution, in principle, consists in using the air-breathing propulsion. There are several alternative development paths: turbojet, ramjet and ramrocket, and in the longer term, air turboramjet and turboramjet.

The adaptation of aircraft turbojets by simplification of the compressor, and of the lubrication and injection systems, and the use of low-cost materials for application where the operational time is limited to several hours, makes this propulsion system competitive with the rocket motors. Currently they are limited, however, to subsonic and slightly supersonic flights.

TABLE 4 *Past and potential development low-signature solid propellants for tactical missiles*

Formulation	Theoretical I_s standard conditions	Density ρ g/cm^3	$I_s\rho$	Estimated date of industrial development
EDB—CDB	229	1.66	380	1970
CMDB	241	1.67	403	1982
XLDB	256	1.76	450	1985
F1	259	1.77	458	1988
F2	261	1.81	472	1993
F3	262	1.83	479	2000

Note: All of these formulations correspond to basic compositions of the CHON type — mixtures of ingredients containing only these atoms — possibly with the addition of low amounts of ballistics modifiers.

The technology of the ramjets and ramrockets is ready for numerous applications to missiles. The systems now developed actually reach ranges of several hundred kilometers [9], and ranges of several thousand kilometers are a possibility being investigated. The development of this type of propulsion is going to take several directions. The integral boosters (in the combustion chamber of the ramjet) without ejectable nozzles (for launching from aircraft in particular) will become widely used on combat platforms, implying such related problems as: design of nozzleless grains, prediction of the performance, and precise thrust vector control. The bonding and thermal protection materials of the combustion chamber will have to be capable of two functions: booster function and very long-lasting ramjet function, for which the temperatures and composition of the gaseous mixtures are very different.

Because of volume and space limitations, the desired increase in range requires the use of high-energy propellants or high volumetric impulse propellant types for the booster phase, and dense liquid fuels or boron or carbon solid fuel-rich propellants for the sustainer phase.

The search for simplicity in manufacture, if not in design, has led to the creation of the experimental model known as the "rustique ramjet" where a single chamber contains both the booster and the sustainer grains. This type of ramrocket has been flight-tested several times in France [10].

The turboramjet is a newer design intended to operate as a turbojet at subsonic speeds and as a ramjet at supersonic or hypersonic speeds. It includes, briefly described: an air intake, a compressor, a turbine, a generator of reducing gases, a combustion chamber, and a nozzle.

The air entering into the motor is compressed by the low-pressure compressor, which is driven by a high-pressure turbine powered by the reducing gases from the generator. The system is capable of accelerating up to its cruising speed, without any additional boosters.

The major advantages of this design are: (1) better thrust and specific impulse, as well as a more stable burning rate than in a ramjet alone; (2) a turbine less complex than the conventional turbines; and (3) a better thrust/weight ratio than with the ramjets.

Among possible applications there are stand-off supersonic missiles, cruise missiles, air-ground missiles, and drones.

3.2.4. *Low vulnerability propellants*

This topic, particularly sensitive for missiles on board ships or on aircraft, requires research into propellants with a low vulnerability to stimuli from projectiles, fire, static electricity, and in addition possessing a pyrotechnical behavior preventing the combustion-to-detonation transition. It is likely that, during the coming years, this theme of "low-vulnerability" propellants will become very important. The most important question, still undecided to this day, will be whether a trade-off with energy performances will be tolerated. It is certain that it will be extremely difficult to significantly lower the vulnerability while maintaining the high levels of performance obtained today, although this is the goal of a large number of important research programs [11,12].

Many of the ingredients being studied for an energy increase in today's propellants could also serve to decrease the vulnerability, for an equal level of energy.

3.2.5. *Processes; decrease in costs*

Decreasing costs is a permanent goal. It is sought both at the level of the design of the grain, by performing value analysis in cooperation with the missile manufacturer to satisfy the operational requirements, and at the level of the manufacture:

- reduction of manufacturing cycles;
- automation of industrial production;
- integrated processing systems;
- selection of materials;
- highly economical, non-destructive quality control tests.

The large industrial production processes already being tested, involve:

- the use of continuous screw extruders: extruded double-base and composite propellants with thermoplastic binders but also now with thermosetting binders;
- the implementation of high production rates, short cycles, and inhibiting techniques;
- high rate of injection systems for composite propellants, and reduction of the cure cycles.

For composite propellants, revolutionary progress (costs decreased by more than half) will be obtained only through extensive modifications of the active parts of the manufacturing process, such as continuous mixing. So far, the difficulties facing this development do not involve basic issues such as mechanical components, but rather the amount of precision required in the continuous feeding of raw materials, and the high level of sensitivity of the propellants to minute variations in the amounts of crosslinking agent, or catalyst. Therefore, progress should come from improvements in the precision of the feeding control equipment, and from the modification of the compositions to render them less sensitive in this area.

4. Propulsion of Shells

An area related to that of tactical missiles, where we will see the use of propellants and semi-propellants increase during the coming years, is the area of projectiles launched from a gun. Increasing the range of ballistic artillery projectiles, and increasing their velocity on the flat trajectory are constant goals.

Beyond the range increase through reduction of the base drag discussed in Chapter 10, research efforts are focusing on air-breathing propelled shells. The major problem consists in placing and having a ramrocket function inside a projectile launched from a gun, and often spin-stabilized. For these, the range of a 155 mm projectile could be increased to 50 km. In the case of a projectile stabilized by tail fins, ranges of 70 km are being predicted. Tubular projectiles, with a kinetic effect resulting from an air-breathing propulsion, are also being studied for anti-tank applications.

At any rate, all solid fuels to be used will have to produce combustible gases capable of burning efficiently in combustion chambers very limited in their lengths. The nature of these solid fuels and the design of these grains will have to overcome problems associated with a gun environment: very high pressures, high initial axial and radial accelerations, and rapid drop of pressure — for instance, when exiting the gun — while ensuring a consistent performance.

5. Space Launchers and Space Motors

This area is one where solid propellants are not doing as well as liquid propellants. All of the following factors have led to a wide use of liquid-fuel rocket engines on heavy launchers: (1) higher levels of specific impulse, and the possibility of easily modulating the thrust; (2) the ability to feed the propellant tanks at the last minute, unlike military missiles, thereby allowing the use of propellants not suitable for long-term storage; (3) less strict volume/weight limitations. Solid propellant rocket motors (Diamant A or B in France, from 1964 to 1972, and the first Japanese launchers, Scout in the USA) were used at the beginning of the space era, either because they were directly derived from the military technology of ballistic missiles, or because the payload was fairly small.

Solid propellant grains continued to be used in two types of motors related to the development of space applications: additional boosters for take-off, allowing an increase in the payload of a liquid propellant launcher (Ariane 3 and 4, for example), and the perigee and apogee motors designed to place satellites on geostationary transfer orbits from parking orbits.

Many motors of this type have been developed in Europe (motors for the MAGE family) or in the United States (STAR family), some of them attaining large dimensions, such as the Inertial Upper Stage SRM-2.

With the American space shuttle emerged an architecture already tested on the Titan III launcher, whereby the whole is designed in such a way that the central liquid propellant motor is not capable of ensuring take-off of the system by itself. At that point, 80% of the thrust is provided by the boosters of the space shuttle. This type of launcher architecture, which utilizes solid propellant grains that are gigantic in comparison with what is used on the larger stages of military ballistics missiles, could become widely developed because the same type of architecture is being considered for the future European Ariane 5 launcher and for the future Japanese heavy launcher (HII).

The mass of propellants involved in these motors (several hundreds of tons) prevented in the past the production of monolithic grains. These grains are consequently case-bonded, and made of segments manufactured separately and later assembled. The propellants used, for reasons of safety and cost are generally polybutadiene-AP-Al propellants.

The progressive use of space for military purposes may confirm this trend toward solid propellant motors: the Department of Defense of the United States defines the main objectives that must be reached by the technologies to be used in the future military space systems as follows:

- immediate availability,
- low vulnerability,
- affordable cost,
- simplified logistics,
- reliability.

These are the very characteristics that have guaranteed the success of the solid propellant motors used on the strategic missiles, leading in the past to a success rate over 90% for American military satellites launched by solid propellant launchers. To this, we may add that, for the very high mass flow rates considered, solid propellants give efficient and easy solutions and that the costs of development and production of solid boosters are lower than with liquids. MacDonald [14] has done a very detailed study of the various possibilities of development of these solid propellant space systems, using either existing motor assemblies, in particular the boosters of the shuttle, or improved-technology motors, focusing in particular on their competitiveness with the liquid fuel engines. More recently the AIAA Solid Rocket Technical Committee has emphasized [15] the potentials of solid rocket motors in the frame of US studies on a future ALS (advanced launch system). The stringent requirements for improvement of cost and reliability related to these applications, and perhaps environmental considerations, may lead to dramatic evolutions of this technology [16].

The present technology used on space boosters is a 20-30-year-old technology based on previous experience in tactical or strategic missile systems. In its most advanced form the propellant used is a composite

propellant: polybutadiene (HTPB), AP, Al with 86-88% solids. This is a low-cost binder with a very good processability; it has a very attractive curing system which gives to the propellant a long pot-life and short cure times and a low viscosity enabling easy casting and high quality. The reliability of the cured propellant grains is good: good mechanical properties are achieved, good liners giving good bonding are available. There is an important experience with tactical and ballistic systems using this type of propellant. It will be used in the Ariane 5 boosters, HII boosters, Titan IV boosters and ASRM for the shuttle.

The processing facilities use batch mixing for the propellant and the nondestructive testing inspection is done with radiographic static controls with a progressive evolution toward automatic dynamic inspection using computer-aided radioscopy or tomodensitometry for exploration of the whole grain.

In their most advanced form these facilities represented by Bacchus West Hercules facility or the facility that is being built in Kourou (French Guyana) for the Ariane 5 boosters have the following characteristics:

- Specialization in the case of the Kourou facility; it is designed to manufacture only the main (100-ton) segments of the booster. This facility is close to the launch pad, enabling minimum handling.
- High level of automatization and computer on-line data acquisition and control.
- Batch processing, using for cost the highest capacity available mixer (1800 gallons, 13 tons of propellant per mix).

For the future continuous mixing is being considered.

Like any transformation industry the solid propellants industry has considered very early [17] the use of continuous processes that would be — compared to the batch processes — more economically efficient and safer, since a smaller quantity of propellant is worked on at a given time. The competition between increased size of the batch mixers and the continuous mixers has been favorable to the batch mixers in the past 30 years, even if Aerojet had operated a continuous mixing facility in the sixties [18].

The situation is changing since Aerojet will use a continuous process [19] for the new improved boosters for the shuttle (ASRM).

The main technical problems involved in continuous mixing have been described in Chapter 10. They are mostly related to precise continuous metering of the raw ingredients and to continuous in-line chemical control of the propellant. A Polybutadiene-AP-Al propellant will still be used.

Other more exotic processes are being researched, but are far less advanced so that their future is unpredictable. Some of them could use thermoplastic elastomers as binder for the propellant; no curing would be needed. A process called MEGABAR uses as oxidizers ammonium nitrate-based eutectic oxidizers which are liquids during the mixing operation, which thus becomes easy and very rapid.

Besides the evolutions that originate because of the work on process improvement some research is devoted to clean or non-polluting propellants [16,20,21].

The AP propellants generate a very high level of hydrochloric gas and aluminum oxide, typically more than 20% of HCl and about 35% of Al_2O_3 can be found in the exhaust gases of our HTPB, AP, Al reference propellant.

The simple solution to the problem is to use an HCl scavenger like KNO_3 or $NaNO_3$. HCl will be replaced by KCl or NaCl in the exhausts. The penalty on specific impulse — a loss of 15-20 s — will be severe. The use of NH_4NO_3 instead of AP would also lead to a severe performance loss. This could be compensated by using an energetic binder — and since in that application we do not want a too-sensitive one — quite a lot of work is devoted to GAP-TMETN binder.

5.1. MONOLITHIC GRAINS FOR SPACE BOOSTERS

The monolithic (non-segmented) boosters could have greater simplicity and reliability, and may have some advantages for cost. The main problems encountered would be [22]:

- the size of the molding tools and mandrels (they could be segmented, etc.);
- the casting of the propellant;
- the handling of these gigantic assemblies (we could imagine that all the operations would be done with the case in the same position until the final assembly, etc.);
- safety problems involved with such big masses of propellant;
- the size of the nondestructive inspection systems;
- the overall cost of demonstrating the validity of the concept.

Other avenues of technological evolution seem to have been opened by the Strategic Defense Initiative (SDI) of President Reagan toward either counter-measures by the "hardening" of strategic missiles and re-entry vehicles, which should lead to a requirement of very high energy and very high burning rate propellants (taking into account the increase in mass), or development of propulsion systems of anti-satellite or anti-re-entry-vehicle missiles, with conventional explosive warheads. The specifications for these systems are not completely developed, although they will certainly lead to:

- Attempts to reduce costs to a minimum, based on the large numbers of launches that may be involved for ground-based interceptors designed to intercept in the high atmosphere or exoatmosphere, or for launching of a large number of satellites at the last minute [23-25].

- Very high volumetric performance and special resistance to thermal cycles for interceptors based on satellites.

6. Conclusions

In the final analysis it appears that, as in many cases, the technological progress of propulsion systems using solid propellants is due at least as much to the expression of new requirements and the emergence of diversified applications, as to the results of basic research disconnected from any requirement specifications.

We have seen that a potential for improvement of the characteristics of solid propellants does exist, and that the development of these characteristics — especially for diversified space applications and the replacement of tactical missiles with newer, more versatile ones — should constitute an important field of study.

The applications of propulsion systems using solid or liquid propellants could also become more intertwined than in the past. We have seen, for instance, the return to bipropellant systems for the upper stages of ballistic missiles, while at the same time large solid propellant boosters were making a breakthrough on space launchers. And while liquid propellants seem to be useless for tactical missiles (with the exception of drone missiles and the possibility of using liquid propellants in a gel form), there will be strong competition for the middle- and long-range tactical missiles between the liquid fuel ramjet, the solid propellant ramrocket, the turbojet and the turboramjet.

Beyond applications to very high-performance military missiles, the emphasis will be placed on costs, particularly for mass industrial productions and very large missiles (artillery rockets and space launchers). This emphasis will not only be on production costs but also on development costs, implying significant changes in the methods of development: systematization of the approach by value analysis done at the pre-design phase; computer-aided automatic methods for the design phase; overtests performed within the framework of the development program, etc.

Finally, three new directions of effort have recently emerged that may have significant consequences on the renewal of the family of solid propellants: low vulnerability research, the various projects related to the American Strategic Defense Initiative and the technology evolution of the new space boosters.

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