CHAPTER 8

The Main Families and Use of Solid Propellants

ALAIN DAVENAS

1. Background

The recent and spectacular development of rocket propellants is in sharp contrast to the slow, even non-existent development of materials for propulsion purposes during previous centuries, when the single basic product, black powder, was not sufficient to propel objects by gas jets, in spite of numerous attempts. At the end of the 18th century the main application of this type of propulsion was for entertainment purposes: fireworks. It was not until the beginning of the 19th century that the military began again to take an interest in rockets.

The great industrial growth of that period promoted their development, and it is clear that the history of propulsion is closely linked to the history of the chemical industry which, in a very short time, offered scientists possibilities for research of new products. The 19th century saw the discovery of new basic molecules, such as nitrocellulose and nitroglycerine, followed by much research designed to master their usage as explosives as well as propellants. The end of that century and the beginning of the 20th century witnessed the emergence of the first modern propulsive powders, today's double-base extruded or cast propellants.

The development of propellants is not, however, linked solely to the development of chemistry; ballistics development was a second essential factor. For 150 years the experts doing research in these specific areas judiciously combined their knowledge and efforts to make rocket propulsion what it is today. In the course of time, other research areas were applied to rocket propulsion: mechanics, thermodynamics, fluid mechanics and industrial technologies, etc.

While the second half of the 19th century witnessed the beginning of the development of today's double-base propellants, known in France as "homogeneous propellants," the second half of the 20th century was characterized by the development of composite propellants containing aluminum and ammonium perchlorate.

Here again, the development was linked to the progress made in chemistry, and in particular to the development of plastic materials, which was very rapid during the Second World War. From 1950 on, polyurethane chemistry found in propellants an ideal area of application. This outlet continues to appear the most significant in industrial terms, as emphasized by Klager [1]. But other systems had been researched before that, and some of their applications are still in existence today, for example the polystyrene–polyesters and polysulfide systems [2], and polyvinyl chlorides [3]. These formulations were developed by large companies, mostly American, who at the time were interested in rocket propulsion. Polystyrene–polyesters, followed by the polyurethanes, resulted from the activities of Aerojet General Corporation and General Tire and Rubber Company. The polysulfides, then polydienic structure products, came from Thiokol Chemical Company and the Jet Propulsion Laboratory. Atlantic Research Company was responsible for PVCs, while Hercules was mostly interested in single and double-base propellants and the possibilities of improving them [4]. Even though, during the past 30 years, the activities of each of these various companies were mainly a function of the sectors of applications they were assigned, they continuously looked for ways to improve performance and link the qualities and advantages of the two basic families. This slowly led to the creation of a new third family of high-energy products, implemented following the typical composite propellant methods, which are known today as composite double-base propellants [4]. Both families were combined and gave birth to high-performance products at the end of the 20th century. Figure 1 gives an overview of this evolution through the major improvements brought to the various families of materials.

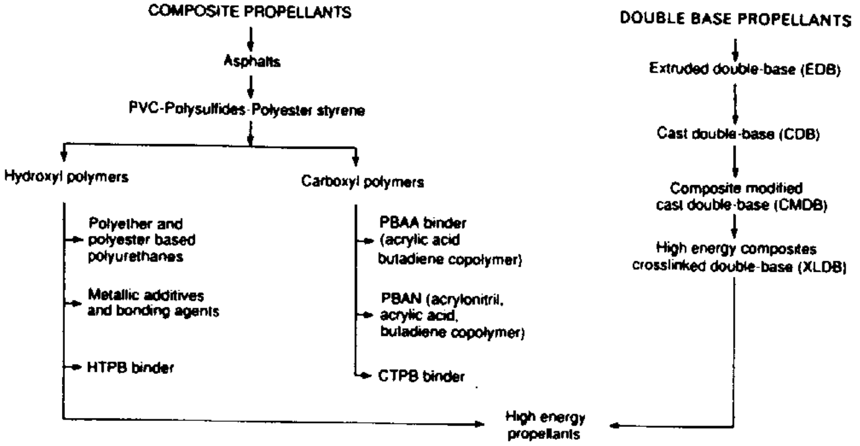


FIG. 8.1. Chronological development of double base propellants and composite propellants.

The development of solid propellants was also accompanied by the development of insulation materials. The research on complementary properties in areas as varied as combustion control, thermal protection of structures, propellant case-bonding, signature, and mechanical behavior, has required the involvement of all sectors of chemistry.

Simplified in the extreme, the development of research in the area of solid propellants has led, as a result, to the existence of two separate major families:

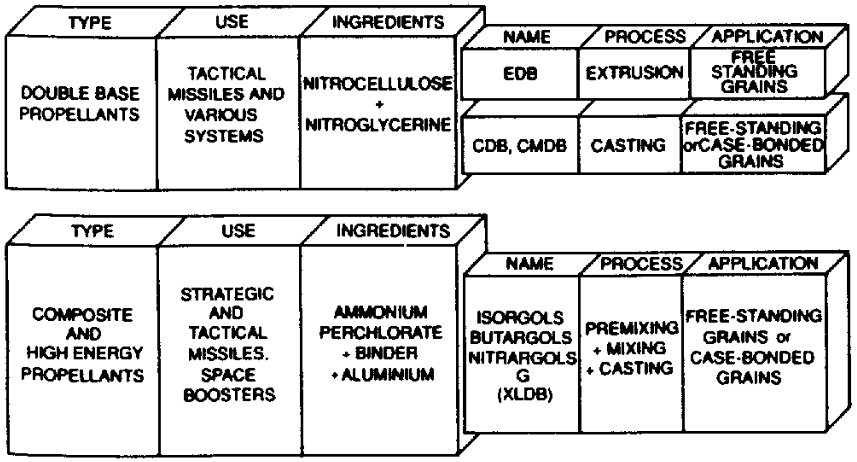
- double-base or homogeneous propellants;
- composite propellants.

Figure 2 provides a basic diagram of their formulation and manufacturing processes.

For more information than is provided by this very quick historical presentation, it will be useful to read the very interesting article published by Lindner [5] in the *Encyclopedia of Chemical Technology*, and in French, the work of Quinchon and Tranchant [6].

2. Utilization in the Propulsion Stages for Missiles or Space Launchers

A color photograph in this book shows the range of industrial grains manufactured by one propellant company, with the various families of propellants grouped according to applications. For each specific application



TYPE	USE	INGREDIENTS	NAME	PROCESS	APPLICATION
DOUBLE BASE PROPELLANTS	TACTICAL MISSILES AND VARIOUS SYSTEMS	NITROCELLULOSE + NITROGLYCERINE	EDB	EXTRUSION	FREE STANDING GRAINS
			CDB, CMDB	CASTING	FREE-STANDING orCASE-BONDED GRAINS
COMPOSITE AND HIGH ENERGY PROPELLANTS	STRATEGIC AND TACTICAL MISSILES. SPACE BOOSTERS	AMMONIUM PERCHLORATE + BINDER + ALUMINIUM	ISORGOLS BUTARGOLS NITRARGOLS G (XLDB)	PREMIXING + MIXING + CASTING	FREE-STANDING GRAINS or CASE-BONDED GRAINS

FIG. 8.2. Propellants: use-composition-process.

the technical or industrial specifications dictated the selection of a particular type of grain, through design work, as explained in Chapter 2. However, general trends do emerge: high-mass grains are made with composite propellants or composite double-base (CMDB) and are case-bonded and those of very low mass are more often made of a homogeneous propellant or smokeless CMDB or XLDB. So we can see that there are some general principles and criteria that guided their selection.

We shall now look at the manner in which the various propellants respond to the general requirements for the propulsion stages of a missile: requirements for performance, physical and mechanical characteristics, signature, manufacturing processes, cost, safety, and vulnerability.

2.1. PERFORMANCE COMPARISON OF INDUSTRIAL PROPELLANTS

2.1.1. *Energy performance*

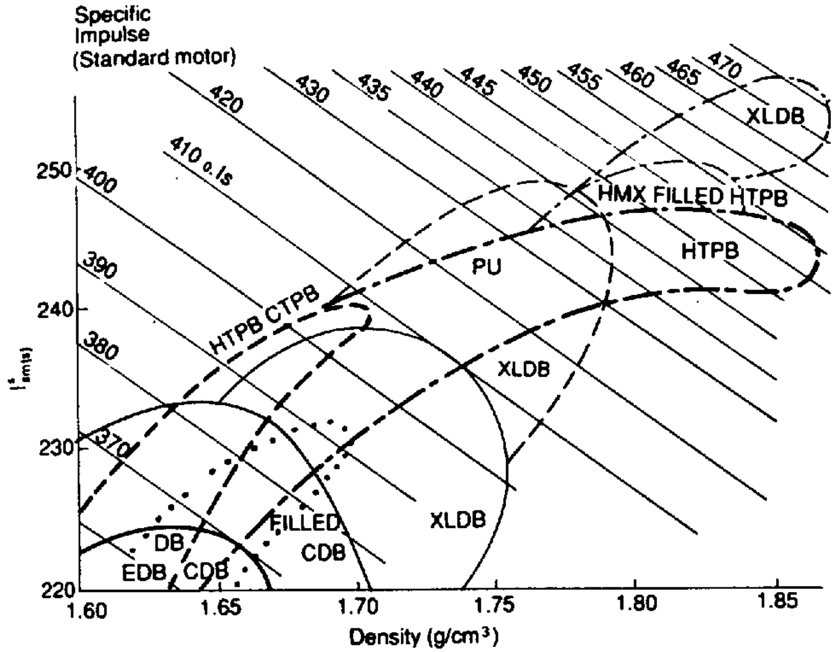
Figure 3 shows the two major energy characteristics of a propellant: the standard specific impulse I^s_{sm}, and density ρ. Very roughly: the greater the product $\rho\, I^s_{sm}$, volumetric specific impulse, which we are using as the energy index, the better-performing the family being investigated.

On the diagram are the family of "low signature" propellants within the visible range, inside which the Nitramites (smokeless XLDB) perform better than the classic homogeneous EDB and CDB and the family of aluminized propellants with approximately 15% greater performance.

To the non-expert an energy difference of 15% might seem insignificant. In real applications, however, its significance becomes much clearer. Take for example a three-stage ballistic missile with a 10,000 km range and typical range differential coefficient, indicated in Table 1 for stage I and II, carrying respectively a 24.5 and 10 ton propellant grain. The related range increase resulting from the higher performance of the first two stages will be 3370 km; i.e. a 40% range increase will be gained by this performance increase on all three stages.

TABLE 1 *Range differential coefficients for the first two stages of a three-stage missile with a 10,000 km range [7].*

	First stage	Second stage
$\frac{\partial P}{\partial M_p}$ (km/kg)	0.4	0.5
$\frac{\partial P}{\partial I_s}$ (km/s)	40	70



XLDB = Nitralane
HMX filled HTPB = Butalane X
HTPB = Butalane
PU = Isolane
XLDB = Nitramite G
CMDB = Nitramite E
PU = Isolite
CDB = Epicète
EDB = SD

SMOKY
REDUCED SMOKE
MINIMUM SMOKE

FIG. 8.3. Propellant characteristics ρ, Is.

Consequently, whenever greater propulsion performance is the primary goal, as is the case for long-range ballistic missiles, space launch boosters, and apogee motors, aluminized composite propellants are preferable.

In the case of tactical missiles a trade-off must be found between performance and signature. It is a delicate trade-off. The search for a reduced signature to prevent early detection of the missile without performance loss has, of course, been the major factor behind the important research done on the nitramite propellants (smokeless propellants based on a nitramine and energetic, nitroplasticized, binder). This criterion might in the future play an increasing role also for ballistic missiles, with the objective of decreasing the possibility of detecting and destroying these missiles.

2.1.2. *Burning rate characteristics*

Limitation of propellant burning rates available for a specific project is one of the most frustrating difficulties for the designer who would prefer the use of the greatest possible range of burning rates.

Figure 4 shows the burning rate range, at a given pressure of 7 MPa for the most commonly used propellants. When seeking the highest burning rates the answer lies with composite propellants for the usual burning times for missile propulsion stages (several seconds to several tens of seconds). However, for very short burning times, on the order of a few tens of milliseconds, which are often used for light anti-tank missiles where a low signature is generally required, EDB (extruded double-base) propellants (solventless) are a prime solution because of their physical properties lending themselves particularly well to designs with thin webs (fraction of a millimeter).

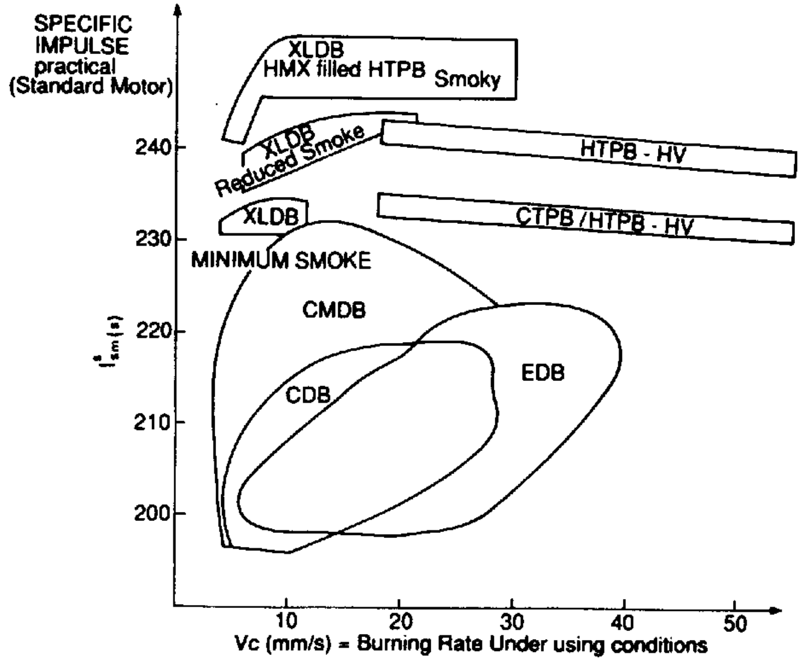


Fig. 8.4. Propellant characteristics.

For very long burning times, solutions can be found in every family, although they are always accompanied by a significant decrease in the energy characteristics.

"Average" burning rate ranges can be obtained with every type of propellant. It is useful to know, however, that EDB propellants offer greater burning rates than the CDBs for an equal level of energy. This is a characteristic inherent in the product (Chapter 9). And again, in applications where a large range of operating temperatures is required, the lower temperature coefficient of the homogeneous propellants may compensate for low rates of specific impulse per unit volume. As a matter of fact, with an identical burning time at 20°C, the propellant with the highest temperature coefficient results in a higher maximum working pressure of the grain at high temperatures, necessitating a thicker structure for the motor, resulting in a weight increase. Similarly, the decreased flow rate at low temperatures can have negative effects because of the resultant reduction in thrust.

2.1.3. *Ducted rocket or ramrockets*

Based on energy performance, the choice between a conventional propellant engine or a ramrocket appears obvious for a tactical missile. But taking into consideration the overall constraints, that choice is no longer as clear, as is demonstrated by the relatively limited number of modern applications (missiles with integrated boosters) in existence today: the Soviet SAM 6 and the French ASMP* with liquid ramjet. But there are some cases where the advantages are obvious [8], as demonstrated in Fig. 5 by a plot of the weight

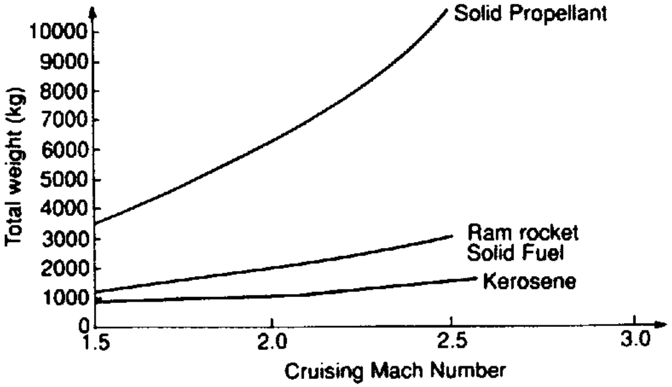


Fig. 8.5. Comparison of propulsion systems.

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* Air, Sol, Moyenne Portée: air-to-ground medium range.

of a missile for a zero-altitude mission with a 100 km range, as a function of the cruising Mach number.

2.2. COMPARISON OF PHYSICAL AND MECHANICAL CHARACTERISTICS

These characteristics very often dictate the feasibility of a given architecture, directly influencing performance (volumetric loading ratio, evolution of grain burning surface versus time) and cost.

2.2.1. *Mechanical behavior*

The mechanical properties of solid propellants are given by the master curves of the parameters S_m, e_m, E_{tg}, and ε, which are explained in Chapter 6 and illustrated in Fig. 6.

These curves reveal three distinctive zones, each related to a specific behavior of the material:

- the glassy zone (Zone 1), characterized by a constant modulus in the short time range, indicating a fragile linear elastic behavior;
- the transition zone (Zone 2), in the interim time range, emphasizing the viscoelasticity of the material;
- the rubber-like zone (Zone 3), in the long time range, with stable behavior of the propellant, which can be represented by a law of the type:

$$E_r(t/a_T) = E \cdot (t/a_T)^{-n}$$

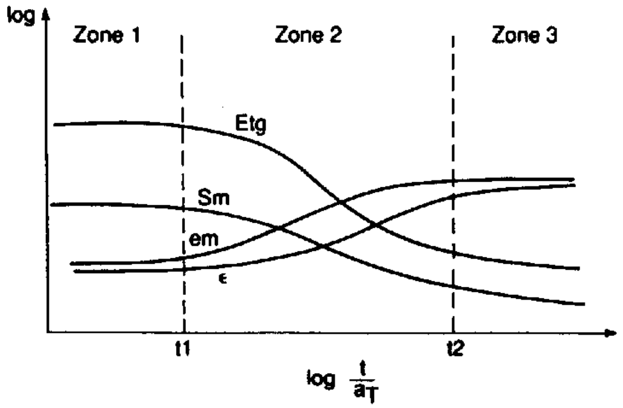

FIG. 8.6. Mechanical behavior of solid propellants.

These three zones are found in all propellant families:

- CDB and CMDB;
- XLDB;
- composites with polyurethane and polybutadiene (HTPB and CTPB) binders.

This allows us to define the following specific parameters:

- width of the transition zone;
- glassy modulus;
- rubber-like modulus.

Width of the transition zone

The transition zone is the zone where the propellant's viscous mechanisms are activated.

The width of the glass transition zone attests to the variety of viscous mechanisms that can be activated. Typical values are given in Table 2, for the various materials.

The glass transition zone of composites and XLDB is reached during load times that are shorter than the usual pressurization times at low temperature. These propellants are therefore very rarely stressed in the glass states.

All propellants show a relatively stable behavior, significant strain at rupture, and a time of relaxation under constant load stress/strain for equivalent times greater than 10^5 min, which corresponds to long-term storage (over 1 year).

Glassy modulus–rubbery modulus

The glassy transition zone is characterized by the values of the elasticity modulus.

The behavior for long times specific to each propellant can be represented by the following type of equation:

$$E_r\left(\frac{t}{a_T}\right) = E \cdot \left(\frac{t}{a_T}\right)^{-n}$$

It is therefore impossible to establish a rubber-like modulus as described for classic linear viscoelastic materials (E = constant). For comparison purposes

TABLE 2 *Width of the glass transition zones of the main propellants*

	Propellant					
	EDB	CDB	PU	HTPB	CTPB	XLDB
t_1 to t_2 (in mn)	10^{-4} to 10^5	10^{-6} to 10^0	10^{-12} to 10^0	10^{-8} to 10^0	10^{-9} to 10^2	10^{-14} to 10^{-2}
Width (tens of mn)	8	5	11	7	10	11

TABLE 3 *Relaxation modulus of propellants for long-term storage*

	Propellant					
	EDB	CDB	PU	CTPB	HTPB	XLDB
E glass (MPa)	2000	1000	3000	300	200	2000
$E\infty(10^7)$ (MPa)	3	1.5	2	0.7	0.5	1.5

between the various propellant families, the modulus at $t/a_T = 10^7$ min is used in Table 3.

The family of propellants we are looking at shows two types of behavior:

- high glassy modulus materials: EDB, CDB, PU, XLDB;
- low glassy modulus materials: CTPB and HTPB composites.

In addition, the transition is much more pronounced for materials that are very stiff at low temperatures than for polybutadiene propellants.

- $E_{\text{glassy}}/E_\infty \sim 1000$ for polyurethanes, EDB, CDB and XLDB;
- $E_{\text{glassy}}/E_\infty \sim 500$ for polybutadiene composite propellants.

The various behavioral criteria examined above provide a glimpse at the behavior of propellants during the various loading zones (firing, storage, etc.). However, to be able to judge the capability of a family of propellants to handle a given load, we will have to analyze the result of a parameter characterizing its behavior.

2.2.2. *Mechanical resistance*

2.2.2.1. *Analysis of the most severe loads*

(a) Long-term storage, thermal cycles, firing/ignition

In long-term storage and thermal cycles, strains inside the grain caused by volumetric variations of the propellants are constant over time for a specific range of temperatures.

This type of loading is similar to a relaxation test (constant strain), and the behavior at relaxation is the parameter that must be studied.

Through experiments we have discovered that the maximum strain during tensile test (e_m) is representative of that behavior.

In the firing of a case-bonded grain, strains are caused by the deformation of the case resulting from pressurization occurring during ignition. This phenomenon is comparable to a tensile test performed under temperature and stress rates corresponding to firing conditions.

Assuming a linear elastic behavior, the resistance parameter will be the pseudo-elastic deformation:

$$\varepsilon = \frac{S_m}{E_{t_g}}$$

Four operating zones will be selected from the master curve of the propellants investigated.

- Firing of a grain for tactical missile at low temperatures:
  temperature, $\theta = -30°\text{C}$ (for example),
  Ignition time: $t_i = 30$ ms.
- Firing of a ballistic or space missile grain at ambient temperature:
  temperature, $\theta = 20°\text{C}$,
  Ignition time, $t_i = 200$ ms.
- Thermal cycles of a grain for a tactical missile:
  minimum temperature, $\theta = -30°\text{C}$,
  storage time, $t = 200$ h.
- Long term storage of a ballistic or space missile grain:
  storage temperature, $\theta = 20°\text{C}$,
  storage time, $t = 10$ years.

The pseudo-elastic deformation at firing and the strain at maximum stress are indicated in Table 4, for all four zones described above.

Cold-temperature firing

The propellants best suited for firing at low temperature, using case-bonded grains, are CTPB and HTPB, and XLDB.

Propellant types EDB and CDB, as well as the polyurethane composite of Table 6, show insufficient deformation capability to withstand the case deformation during firing.

TABLE 4 *Propellant mechanical capability at firing and under thermal stress*

	Propellant					
	EDB	CDB	PU	CTPB	HTPB	XLDB
Low-temperature firing $\varepsilon(\%)$	4.3	2.8	2.4	5.6	6	8.1
Ambient-temperature firing $\varepsilon(\%)$	4.3	10.5	16.5	12.5	13	13.5
Cold cycle $e_m(\%)$	18.5	42	40	35	38	80
Long-term storage $e_m(\%)$	24	60	20	35	42	60

From a mechanical point of view they can be used only for free-standing grains which are subjected to less stress at low temperatures.

Ambient-temperature firing

The HTPB, CTPB, polyurethane, CDB and XLDB propellants have a greater capability than the EDB. Therefore, they will show a better mechanical behavior at ambient temperature firing of case-bonded grains.

Cold thermal cycle

The CDB, polyurethane, CTPB and HTPB and XLDB propellants have maximum strain above 35%, and consequently good mechanical resistance to thermal cycles.

The elongation capability of EDB is definitely smaller ($e_m \sim 18\%$), and could, as a result, lead to some risks of rupture during severe thermal shock, even for a free-standing grain structure.

Long-term storage (Fig. 7)

In this stress–strain situation typical of case-bonded grains HTPB, CTPB, CDB and XLDB the best mechanical capability.

Even though CDB has a great deformation capability we cannot place it ahead of the other propellants for this type of load, because the thermal expansion coefficient plays a significant role, leading to an increase of the thermal stress in the grains:

$$\alpha_p \sim 1 \times 10^{-4} \quad {}^\circ\mathrm{C}^{-1} \text{ for composites}$$
$$\alpha_p \sim 2 \times 10^{-4} \quad {}^\circ\mathrm{C}^{-1} \text{ for CDB}$$

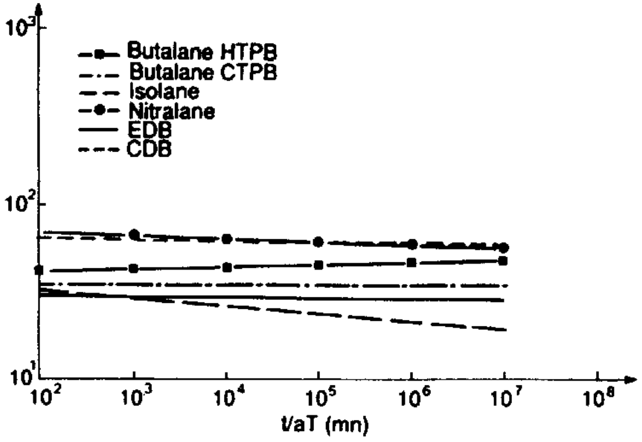

FIG. 8.7. Long term storage behavior of various propellants.

2.2.2.2. *Conclusions*

Analysis of the various parameters of the behavior and strain capabilities of the main propellant families provides us with the following conclusions:

- *Propellant grain for tactical missiles.* From a strictly mechanical point of view, only the polybutadiene and XLDB propellants can be used for case-bonded grains, because of their good mechanical resistance during firing at low temperatures. EDB and CDB propellants, as well as the polyurethane propellant discussed above, can be used only for free-standing grain, because of their high modulus and their low capability for deformation under this particular stress. In this type of design, mechanical resistance to thermal shocks is greater for CDB than for EDB propellants.
- *Propellant grain for ballistic motors/missiles:* = 20°C. The CTPB, HTPB, polyurethane, CDB, XLDB propellants can be used in case-bonded grains. However, CDB demonstrates the lowest mechanical resistance to firing, as well as to long-term storage, due to its high thermal expansion coefficient. The capability of the polyurethane tends to decrease under long-term storage: therefore the HTPB and CTPB and XLDB propellants are preferable.

2.3. COMPARISON OF SIGNATURES AND SIGNATURE CHARACTERISTICS

The most dramatic aspect is, of course, the visible signature which marks the launching of a ballistic missile or the space shuttle with a huge plume of white smoke. That visible smoke is characteristic of propellants with aluminum (primary alumina fumes). More generally, it is characteristic of metallized propellants and in the case of ammonium perchlorate composites without aluminum of the recondensation of hydrochloric acid when the suitable ambient temperature and humidity conditions are present (secondary smoke).

Figure 8 shows the smoke occurrence, and illustrates its intensity for various propellants under average climatic conditions in Europe.

In the case of a missile target that is followed visually, these smokes completely mask the target and are absolutely unacceptable. As a result the first generations of anti-tank or ground–air missiles were forced to use homogeneous propellants. Today, these could be replaced by Nitramites (minimum smoke XLDB propellants).

Today's guidance systems rely mainly on the interaction of the plume with laser beams within the infrared frequencies, requiring low absorption by the combustion gases in the corresponding frequencies. Similarly, the infrared signature resulting from the plume emission is often related to afterburning in the atmosphere, which should be decreased or eliminated. The related criteria

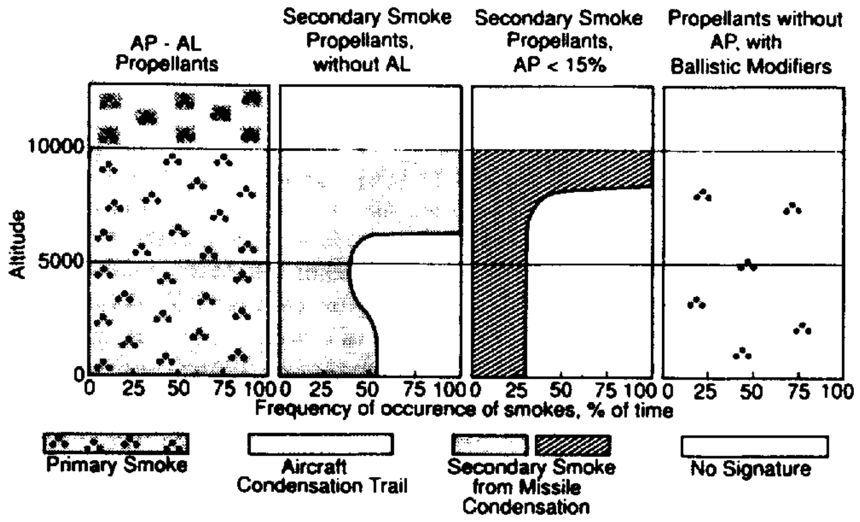

FIG. 8.8. Appearance of visible signature of missiles in a European climate.

are more subtle. Some of the characteristics of plume emissions of propellant gases are indicated in Chapter 5, and can provide initial direction.

2.4. COMPARISON OF MANUFACTURING PROCESSES AND COSTS

Figure 2 gave an overview of the flow-chart for the production of propellants.

EDB grains obtained by extrusion are clearly limited in their mass and size. These limitations are mainly due to the size and the performance of the presses that can be used. Diameters are generally limited to 250 mm in the Western world.

Similarly, only cylindrical grains simple to manufacture, and therefore inexpensive, can be produced.

The EDB process, on the other hand, lends itself particularly well to industrial production as well as to high production rates. It is therefore particularly suited for the production of small ammunitions, and for various non-military applications. The homogeneity of this product and its high degree of rigidity, allowing the production of very thin webs as well as the possibility of machining within very precise limits (a few hundredths of a millimeter), makes it very useful when seeking high-precision impulses. In addition, the combination of rigidity and very thin webs is attractive for grains combining short combustion times with high accelerations — useful for light anti-tank missiles.

Finally, processes such as continuous screw extrusion and stamping may well give new impetus to this product by contributing to a decrease in costs or improvements in working conditions, production rates, or geometry (see Chapter 9).

The CDB and CMDB propellants have the advantage of allowing the production of free-standing grains in any type of shape with performances that are comparable to that of the EDBs. Free-standing grains weighing several tons manufactured by this process were used on propulsion stages of US missiles. In France, free-standing grains weighing several hundred kilograms are used in the sustainer motors of the Exocet missile family.

2.4.1. The industrial cycles

The length of the production cycle is of critical importance for the client. It is, of course, determined not only by the type of propellant but also by the production capability available and by the number of specific tools and equipment required for production.

All things being equal, a classification of the length of production cycles would be in the following increasing order: EDB, composites or XLDB, CDB (or CMDB).

The production of EDB grains with selected raw materials is almost instantaneous as they are thermoplastics shaped directly. The length of the cycle is controlled by finishing and quality control operations.

At the other end of the scale, the production of CDB is very slow, requiring various intermediate production steps, as well as ballistic adjustment of the casting powder, requiring firing test controls on specially cast specimens.

The decision to select a free-standing grain or a case-bonded grain is, of course, greatly dependent on the industrial production of the motors. In the case of free-standing grains the production of the cases and of the grains can be done separately, allowing the creation of buffer stocks in case of production difficulties in one of the other production lines.

2.4.2. Costs

The issue of the cost of propellants is important both for the client and the manufacturer; it is also the object of many controversies.

Without pretending to do an in-depth analysis of this problem, it may be useful to look at the subject and to determine several major factors. The cost of a propellant grain is linked to four main parameters:

- cost of the raw material;
- manufacturing process;
- quantities required and delivery schedules stipulated;
- technical specifications, including conditions for acceptance and control.

Of course, there is an interaction between the selection of the propellant grain (and its manufacturing process) and the specifications requested by the client. A constructive dialog is necessary to avoid certain specifications unnecessarily increasing the complexity and thereby the cost of the propellant grain.

- When the volume and the duration of the manufacturing process allow the organization of a specific production facility (as in the case of the MLRS), the cost may decrease significantly.
- The cost of raw material may also be an essential factor, e.g. XLDB using HMX of very specific particle size, or special nitrate esters (BTTN) are intrinsically more expensive than a simple composite propellant.

Cost comparisons between various supplies in various countries are difficult for at least two reasons:

- the quantities required and production schedules are rarely the same;
- the rules followed to determine cost (e.g. amortization rules, raw material sometimes supplied free by the Government, investments that are or are not compensated by the client) vary greatly.

Finally, the calculations are often expressed in terms of the cost of the complete motor, and not of the propellant grain.

This raises the very interesting issue of the relative costs of various services involved in the production of a rocket motor.

Gaunt has done an analysis of that issue [9] for ballistic missiles and motors for space launchers. Figure 9 shows that the grain averages approximately 27% of the total cost. This ratio is very similar to observations made in France. In these two specific cases, nozzles and the thermal protection are especially expensive; that ratio is usually much smaller for tactical missile motors with a less sophisticated rear assembly, in which case the grain cost can be as high as 50% of the total.

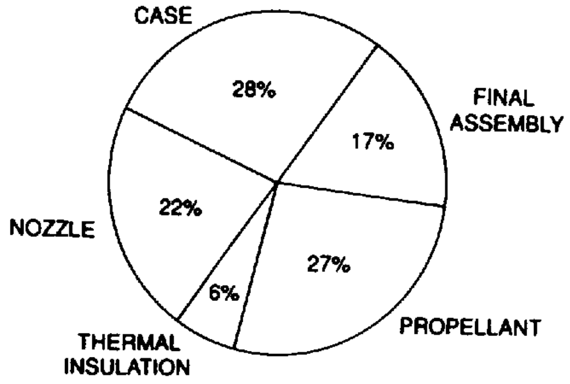

Fig. 8.9. Breakdown relative costs for a large motor.

The same analysis demonstrates that the principal component of the production cost for today's rocket motors is labor (an average of 55% of the total cost). Cost reduction is obtained through intensive automation, requiring heavy investments that can only be amortized if very large programs are launched.

Finally some simple things can be said for the cost of the different propellant families:

- For composite propellants, the mass of propellant has a very important effect on the price of propellant per kilogram.
- A precise comparison can only be obtained on a specific project. For instance, for a small propellant grain (a few kilograms) for an anti-tank system, we compared the cost of an EDB and CDB solution, both compatible with the specifications, and discovered that their predicted cost was so close that it was impossible to consider this parameter for the final choice.

2.5. SAFETY AND VULNERABILITY CHARACTERISTICS

The client, whether the integrator or the end-user, is particularly interested in these characteristics because they are the determining factor for size of final assembly facilities, storage areas, conditions for transport, and handling and operations. The operational risks vary with the setting: for example, the use of missiles under war conditions, or for space launchers, the risk of lightning strikes on the launch pad, etc.

Here again, we must emphasize the relative and somewhat arbitrary nature of individual national regulations that complicate attempts to establish comparisons at an international level. Although the regulations tend to be similar in their hazard classification of explosive substances, the classification methods are not the same. An identical propellant or grain — CMDB, for instance — can be found in a class 1.1 in the US (liable to detonate), and class 1.3 in France (see Chapter 7).

In addition, these classification tests were established for production, storage and transportation purposes. Reactions to stimuli in operational conditions are not necessarily well characterized by these tests.

For several years, in the wake of serious incidents, or accidents that took on catastrophic proportions such as those on the American aircraft carriers *Forrestal* and *Nimitz*, emphasis has been placed on the concept of "lower sensitivity munition". Missiles conforming to this designation will be considered as "reduced risk ammunitions" (Munitions à Risques Atténués — MURAT — in French) and "insensitive ammunition" in English.

2.5.1. *Pyrotechnic threats from munitions*

All munitions containing any energetic material (the term "munitions" refers to armament devices of any caliber and includes mines, torpedoes, missiles, and rockets) present pyrotechnic threats. Any munition that has been subjected to unplanned stimuli (e.g. from a bullet or a shaped charge) is not only likely to have been damaged, but its energetic material (gunpowder, propellant, explosives) will probably also deteriorate or react. The reaction of the munition generates thermal fluxes, a release of debris and shock overpressures in its surroundings. The detonation of the first munition can induce a reaction in other munitions nearby. The ensuing disaster may result in the loss of the carrier, known as the combat platform (e.g. tank, helicopter, aircraft, warship, aircraft carrier) with munitions aboard.

2.5.2. *Survivability of the combat platform*

Today, these platforms are extremely expensive, and as a result are limited in number. Defense organizations in various countries are greatly concerned with the improvement of their survivability. Such an improvement involves:

- diminished detectability;
- diminished probability of being hit, once detected;
- reduced severity of the damage, once the platform has been hit.

The general improvement in the survivability of land, air, and sea platforms is a major aspect of armament modernization. It requires a minimization of the effects of explosive hazards from munitions subjected to unplanned stimuli, contributing to the reduction of the vulnerability of the platform by limiting the severity of the reaction and subsequent damage in a credible event.

2.5.3. *Basic corrective measures*

These are as follows:

- protection with materials designed to reduce the impact of the stimuli, barriers to slow down or prevent the propagation of the disaster, and adapted storage configuration;
- intervention devices, including flooding, more or less automatic;
- modification of the cases containing the energetic material (for example, pressure relief systems).

2.5.4. *Need for improvements*

The above measures have the advantage of being rapidly implementable. Unfortunately, their application is not always practical. Protective materials are often heavy, cumbersome, and they hinder the operation of the munition.

Worse yet, these remedies can, over time, turn out to be useless. The great variety of scenarios of credible events makes it particularly difficult to demonstrate the efficiency of these measures.

As a result, the expected minimization of severity could prove entirely misleading. Recognizing this, various defense organizations and industry leaders began to consider the possibility of lowering the sensitivity of munitions, the third step in this process. Progress made in the area of chemical explosives for nuclear warheads and explosives for mining and demolition suggests the possibility of having munitions that reliably fulfill their performance and operational requirements, but which are designed to minimize their sensitivity.

2.5.5. *Lower sensitivity munitions or insensitive munitions*

The design of these new munitions, particularly at the research stage, must be based on the following conditions:

- specially designed cases;
- revised inner configuration;
- energetic materials with limited reaction.

The last of these conditions, alone, could provide a satisfactory solution to the problem, provided, however, that the survivability is not adversely affected.

Specifications have already been introduced by the US Navy, the prime force behind this activity. The related tests and criteria are shown in Table 5. For propellants, the following data must be determined and provided:

- Test results for:
    - slow cook-off,
    - fast cook-off,
    - sympathetic detonation,
    - impact from multiple bullets,
    - impact from multiple fragments;
- Critical diameter data.

The threat of fire, alone, is generally considered acceptable if thermal explosions, and particularly detonations, are prevented.

TABLE 5 *Tests and criteria for lower-sensitivity munitions*

Slow cook-off	No reaction greater than fire
Fast cook-off	No reaction greater than fire
Bullet impact	No reaction greater than fire
Sympathetic detonation	Unacceptable for storage
Sensitivity to electromagnetic radiation	No explosive reaction

Systematic research has been undertaken in various countries with the purpose of establishing or completing the characterizations of existing energetic materials. This research sometimes leads to unexpected results, and the meaning or consequences of those results remain to be determined. An example is significant variations in the critical diameter of polybutadiene-AP-Al propellants according to the percentage of ferrocene derivative in the formulation [10]. All composites with ammonium perchlorate propellants show very poor results in the slow cook-off tests.

It is too soon yet to have formed any conclusions on the respective merits of existing propellants. A new perspective must be gained, and it will take several years. Most likely, no existing propellant providing sufficient energy will ever satisfy all requirements. For example: a sub-critical detonation geometry requirement for double-base grains or XLDB could lead to a considerable energy loss for smokeless propellants. However, various labs are working on the development of lower-sensitivity high-energy smokeless propellants, based on logical decisions such as those illustrated by Fig. 10.

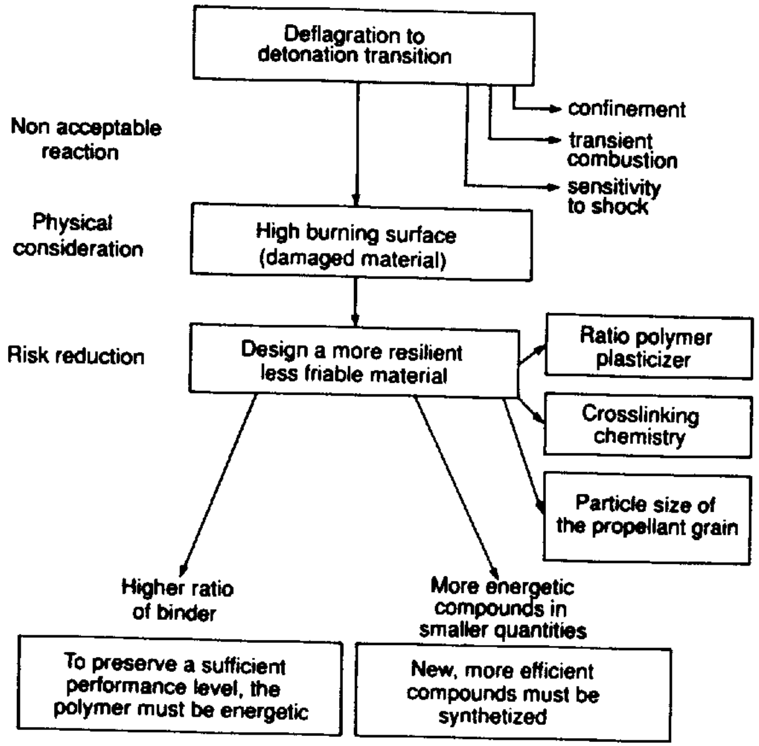

FIG. 8.10. Demonstration of how the formulation of an energetic material can reduce the threats.

3. Additional Propulsion for Artillery

Increase in range and improvement of the accuracy of impact are two major concerns in the design of artillery munitions. A technical solution to satisfy these requirements consists of the injection, at low rate, of gases in the vicinity of the base of the shell, to compensate partly or entirely for the aerodynamic drag of the base.

The location of the ejectors will determine the selection of the configuration:

- The systems with ejectors located at the very base of the projectile are commonly known by the English term "base-bleed" [13]. This configuration is illustrated in Fig. 11.
- The systems with ejectors located over the perimeter of the afterbody, ejecting gases in the outer supersonic flow area, are termed external combustion.

A description of the base-bleed system follows:

3.1. PRINCIPLE FOR THE DECREASE OF BASE DRAG

In modern artillery, base drag is 30–50% of the projectile total drag. It is represented by the nondimensional coefficient, C_x base, expressed by the

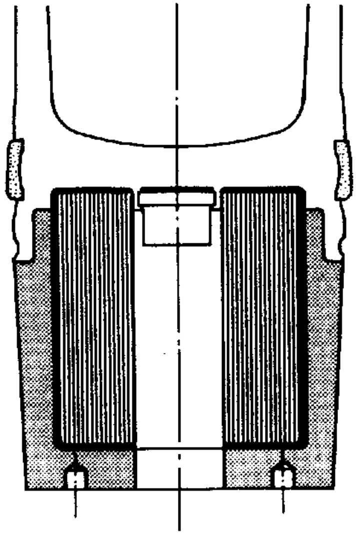

FIG. 8.11. Aft-end of a shell equiped with a base-bleed generator.

formula:

$$C_x \text{ base} = \frac{p_\infty - p_{\text{base}}}{\frac{1}{2}\rho_\infty V_\infty^2}$$

where p, ρ, and V stand for pressure, density and speed of supersonic outer flow, base, base pressure.

By ejecting gases at a low rate directly into the low-pressure zone, the base pressure can be raised, thereby decreasing the C_x base drag coefficient.

The model of drag correction selected for combustion of a base-bleed grain is taken from the works of the Swedish scientist, Hellgren [14].

C_x corrected: C_x total − C dec. C_x base
with C_x total: Total drag coefficient without base-bleed
C_x base: Drag coefficient without base-bleed
C dec.: Decrease factor for the base-bleed effect.

The C dec. parameter is, essentially, a function of flight conditions, rate of exhaust gases, and the shape of the afterbody.

The drag reduction effects increase with the V_0 initial speed of the projectile. The increased range of a maximum range firing is estimated at:

$$+20\% \text{ for } V_0 = 800 \text{ m/s};$$
$$+25\% \text{ for } V_0 = 900 \text{ m/s}.$$

3.2. OPERATION SPECIFICATIONS FOR A BASE-BLEED GAS GENERATOR

The base-bleed gas generator is designed to satisfy the following specifications:

- The internal configuration of the grain allows a highly regressive burning surface versus web burnt, in order to obtain conditions of ejection during the combustion while the missile is on its trajectory, so that the characteristic or reduced flow rate is close to $q = 5 \times 10^{-3}$.
- The effect of mass injection at the base is defined by this adimensional coefficient, called the characteristic flow rate:

$$q = \frac{m_b}{\rho_\infty V_\infty A_b}$$

m_b = mass flow rate of the combustion gases injected to the base;
V_∞, ρ_∞ = speed and density of the surrounding air;
A_b = surface of the base.

- To maintain the subsonic flow of the combustion gases, the pressure generated inside the chamber must stay in the subatmospheric pressure range. The composition used must offer satisfactory combustion stability at this pressure range. Based on the firing conditions, the burning rate level will be situated between the range of 1 and 1.5 mm/s at 0.1 MPa.
- The reducing combustion gases mix with the air of the outside flow and cause a re-ignition phenomenon. This addition of weight and energy close to the base reinforces the pressure increase effect.

  The mechanical properties of the propellant are optimized so that the generator can survive the stress induced in the cannon bore, where the pressure and acceleration levels are very high.

  The propellant selected allows operation within a wide range of temperatures: −45 to +60°C.
- As a rule, the materials and the implementation process are selected with the idea of using industrial capabilities that are compatible with large series production, with costs known to be acceptable in the artillery sector, i.e. costs that are lower than those acceptable in the case of missiles.

  This type of production satisfies therefore two major criteria:
  - limited cost and production time;
  - manufacturing process easily adjustable to the various calibers used in the artillery sector.

  An acceptable solution that satisfies all of these specifications is a gas generator made of a composite propellant (Butalites, i.e. reduced smoke HTPB).

3.3. ROCKET-ASSISTED PROJECTILES

Another solution to increase the speed of the projectile on path is to apply a thrust provided by the combustion of a rocket motor. These are known as rocket-assisted projectiles: RAP.

The rocket motors necessary for an effect comparable to base-bleed are very large and heavy, limiting the amount of explosive in the shell.

Finally, various countries are researching ramrocket or ramjet shells, with the purpose of either increasing the range of classic artillery [15], or propelling anti-tank arrow-piercing projectiles. This is expected to be fairly long-term research.

4. Gas Generators and Their Various Applications

The first systems moved by gas generated by propellants or powders made their appearance during the Second World War, in German combat aircraft with ejection seats in 1944.

Propellant cartridges had also been successfully used to help in the starting of piston-engine aircraft. A propellant cartridge with a high burn rate was ignited in the engine combustion chamber, resulting in the starting of the entire device.

Since that time the use of gas generators has greatly expanded, and today they have numerous applications in the aeronautics and space sectors, in military missiles, and in some commercial activities [11,12].

These gas generators can be used in conjunction with many other existing energy sources, such as:

- gas turbines;
- internal-combustion engines and electric motors;
- compressed gases and hydraulic accumulators;
- flywheels;
- batteries and fuel cells;
- solar cells.

These energy sources provide relatively varied application times, working power levels, and density of stored energy.

The gas generators are classified in four major categories, based on the type of propellants used:

- solid propellant gas generator;
- hybrid gas generator;
- liquid monopropellant gas generator;
- liquid propellant gas generator.

Further in the text, we cover only the solid propellant gas generators capable of producing energy only once, for periods of times ranging from fractions of seconds to several minutes at the most. These generators can nonetheless be controlled, regulated, and in some cases even stopped and started several times, although these latter types of generators are much more complex.

There are several types of solid propellant gas generators, based on their application:

- Highly reducing gas generators used to produce gases to be burned in a second step with the oxygen in the air. This class of generators include essentially solid fuel generators used on ramjets.
- Hot gas generators designed to produce gases used to activate power units such as hydraulic turbines, alternators, pumps, cylinders actuators, etc. or to ensure auxiliary propulsion. In systems of this kind, the exhaust gas temperatures of the generators are generally higher than 900–1000°C.
- Cold gas generators designed to supply gas to pressurize or inflate systems incapable of handling high temperatures; in such cases the temperature of the gas when it is used must always be lower than 300°C, sometimes even below 100°C, requiring the use of cooling devices for the initial gases.

The propellants used for these various generators have a formulation similar to the classic solid propellants. Either homogeneous propellants or composite propellants can be used, but the use of the latter is more prevalent these days.

The technology and materials used determine the performance of each of these various energy sources. Table 6 gives a list of energies that can be produced by gas generators and by various competing systems.

We see here that gas generators are perfect choices for short operation times of less than several minutes. According to the sort of energy required, compressed gas and flywheel can also be used. Since the use of a gas generator does not require the use of any valve, and it can be ignited by a pyrotechnic device, the gas generator can be smaller, lighter, and offer quicker reaction

TABLE 6 *Comparison of various energy sources in terms of applications and available energy*

Energy source	Applications	Available energy (in kW) range
Gas generator	Auxiliary propulsion Inflation Liquid propellant tank pressurization Thrust vector control	0.5 to 1000
Gas generator with turbine	Hydraulic energy Engine starter Fuel pump	0.5 to 100,000
Gas generator with turbine generator	Auxiliary energy units for aircraft, missiles or space shuttles	0.5 to 1000
Gas turbine	Transportation (ground, air, sea) Auxiliary power units Stationary energy	50 to 10,000
Internal combustion engine	Transportation (ground, air, sea) Stationary energy Leisure vehicles Portable tools	5×10^{-3} to 1000
Pressure gas	Auxiliary propulsion Inflation Propellant pressurization	0.05 to 100
Flywheel	Toys Public buses Machines	5×10^{-3} to 100,000
Batteries	Lighting Toys Engine starter Emergency power	5×10^{-8} to 10 (per unit)
Fuel cell	Energy for astronautics Stationary energy	0.05 to 10 (per unit)
Electric motor	Hand tools Toys Vehicles	5×10^{-4} to 100,000
Photovoltaic solar cell	Energy for astronautics	5×10^{-3} to 20

times than a compressed gas system. The problems caused by exhaust pressure, temperature, and chemical composition can constitute, however, an obstacle to their use.

When compared to a flywheel (rotating energy), the gas generator coupled with a turbine has the advantage of always being ready to use.

The gas generator is a serious competitor to the gas turbine for utilization times greater than 1 min, provided the total power required is less than 150 kW and the total operating time does not go beyond a few minutes.

When operation takes place without atmospheric oxygen, gas generators are superior to all other systems, regardless of the operating time requirements.

The advantages over batteries can be demonstrated in the case where the power required is relatively high (several hundreds of watts). It would include the following uses, for example:

- composite propellants for power generators for ballistic or tactical missiles;
- EDB propellant to propel submarine missiles out of their containers;
- EDB propellant, or CDB, for pressurization of liquid propellant tanks;
- composite propellants supplying very low CO contents for inflatable air-bags used in case of collision in some automobiles (generally based on NaN_3 propellants).

5. Pyrotechnic Compounds and Propellants for Ignition Systems

The various pyrotechnic elements forming an ignition system for a propulsion grain were introduced in Chapter 1: primary initiator, ignitor initiator, and main ignition grain. For a detailed description of these components, consult a pyrotechnics dictionary [16]. Table 7 provides a description of the composition of an ignition system, and a typical igniter is shown on Fig. 12.

The function of the main grain is to deliver a significant amount of hot gases or a large number of hot particles in a very short time, a few tens of milliseconds.

This rapid generation must satisfy two requirements necessary for the ignition of the propulsion grain [17], as follows:

- creation in the volume surrounding the grain of thermodynamic conditions (constitution of the gaseous phase, pressure, temperature), close to the conditions of the grain's steady combustion state;
- ignition by heat transfer of the igniter toward the propellant through convection (transmission of heat flow), radiation (solid particles), or conduction through solid or condensable particles;

TABLE 7 *Constitution of an igniter: most commonly used components*

Grain type to ignite	Initiators	Increments or main grain initiators	Main grain igniter
Large	Electric with high energy level and ignition threshold; operated by shock-wave or laser and pyrotechnic compounds.	Easily ignited pyrotechnic composition, powder or pressed, and usually generating a gas rate adapted to the main grain.	Free-standing case-bonded grain with high burning rate composite or EDB propellant.
Small	Usually electric.	Same type, although often integrated with the initiator.	*Either*: same principle as for large grains: ignition with a micro rocket EDB propellant or fast-burning composite.* *Or*: pyrotechnic compound for ignition generally compacted.

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* In such cases, the ability of the propellant to ignite is so high that it is possible to do without the increment grain.

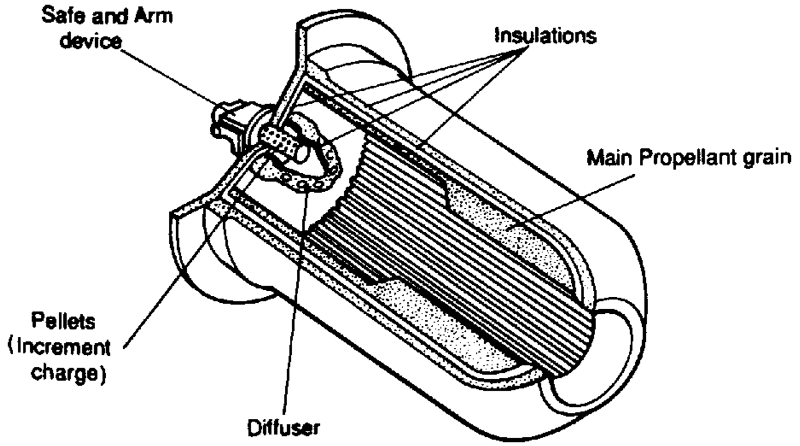

FIG. 8.12. Typical ignition system.

- component selection and design of the igniter can be done on the basis of operating specifications (volume, ignition time, position in the motor, safety, and cost).

Propellants

When the main ignition charge needs to be significant (ignition of large grain), it will take the form of a small propellant grain. This grain must present a large combustion surface which, coupled with a high burn rate, will deliver a high flow rate. Composite or EDB propellant are particularly well suited for this function.

Granulated or pelletized pyrotechnic compositions

These are used for initiator, increments and main charge in the case of small grains, for which the volume to be pressurized is small. They are discussed in Section 5.1 below.

For each of the pyrotechnic materials, the following information is necessary:

- combustion temperature;
- flame temperature;
- nature of the combustion materials, and related gaseous volume;
- ignitability;
- safety characteristics.

5.1. FORMULATION, COMPOSITION AND CHARACTERISTICS OF THE PYROTECHNIC MIXTURES

The powder or compact mixtures are composed of a fuel (metal) and an oxidizer (oxide or fluoride) [18]. Once initiated, they are subject to a very exothermic oxidation-reduction reaction.

The combustion translates itself into the progression of a reaction zone which separates the reacting elements from those which are not reacting yet. The burning rate, i.e. the pressure rise time, is a function of the particle size and of the reactivity of the oxidizer and the fuel.

Ignition mixture families and their main characteristics

Six major families exist today, with two or three elements each, and differentiated by the fuel and oxidizers that are used. The first family (black powder) is very old; the others were developed in conjunction with the propellants.

The elements and major characteristics of these six families are as follows:

(a) Black powder

Black powder is a mixture of three ingredients: potassium nitrate (75%), sulfur (12.5%) and charcoal (12.5%). It dates from antiquity and is still used today as a powder or pellet ignition powder.

It is not very powerful (775 cal/g), highly gaseous, and easily ignited (except in a vacuum).

(b) Aluminum and ammonium perchlorate mixtures

A powder mixture of aluminum flakes (40%) and ammonium perchlorate (60%) powder. It is a very energetic composition (2500 cal/g), with a high rate of gas generation, good ignitability, highly sensitive characteristics, and a burning rate greatly affected by confinement.

(c) Aluminum, potassium perchlorate mixture

A mixture of two aluminums in flakes, with different reactivity (35%), with potassium perchlorate (64%), and aluminum stearate (1%). This mixture can be used in a powder form, although it is more often compressed into pellets, 1 to 6 mm thick. The aluminum stearate acts as a binder.

It is a very energetic composition (2500 cal/g), highly gaseous, possesses very good safety characteristics, but is difficult to ignite, and its burning rate is very dependent on pressure.

By modifying the ratio of the two types of aluminum it is possible to modify the powder's burning rate, and consequently the ignition characteristics (time and pressurization).

(d) Zirconium-oxide mixtures

These are primarily binary mixtures of zirconium (37%), with copper oxide (63%), or quadruple mixtures of zirconium (45%), with barium chromate (34%), ammonium perchlorate (14%), and ammonium bichromate (7%).

These mixtures are used in the form of powders. They are moderately energetic (700 to 1000 cal/g), but offer very good ignitability. They are, however, very sensitive to electrostatic discharges.

The mixtures including CuO produce little gas but a large number of hot particles. Mixture with barium salts and potassium yields a high volume of generated gas.

(e) Boron and potassium nitrate mixtures [19]

These are essentially boron and potassium nitrate mixtures used in the form of powder, or pellets or compact mixtures of nitrocellulose, boron and potassium nitrate used in the form of micro-rockets.

These mixtures are moderately energetic (1500 cal/g), highly gaseous, have very good ignitability and excellent safety characteristics. Their main drawback is their hygroscopicity.

(f) *Magnesium–teflon–viton mixtures [20]*

These powerful mixtures (2200 cal/g) can be compressed or extruded. Not very gaseous, and with a moderate flame temperature, they offer very good safety characteristics but are difficult to ignite.

The main performance and safety characteristics of these four typical compositions are shown, respectively, in Tables 8 and 9.

5.2. MANUFACTURING PROCESSES

5.2.1. *Powders*

The homogeneity of the powder mixtures is obtained by using a mixer of solids which consists of, for example, two containers and a rotation system outside of the mixing zone. After drying has occurred, the oxidizers are placed in one container, and the fuel in another. The whole is rotated for approximately 1 hour to ensure good homogeneity of the products. For safety reasons all operations, including dividing into small quantities, weighing, and closing of the containers, are done remotely with the use of a mechanical remote control device.

5.2.2. *Compacting*

After homogenization the powder mixture can be compacted into pellets of different sizes.

This operation is done with an automatic pellet machine with mold plate. The various operations, including filling of the mold, molding, compression, and ejection of the pellet, are done remotely and continuously.

The quality of the compacting is controlled through a crash resistance test of the pellets.

TABLE 8 *Performance of four powder mixtures*

Mixture	Flame temperature (K)	Energy (Cal/g)	Volume of gases released (l/g)
Aluminum and ammonium perchlorate	4500	2500	6.0
Aluminum and potassium perchlorate, and aluminum stearate (compacted)	4500	2500	4.0
Zirconium and copper oxide	2500	700	0.4
Zirconium and barium chromate, and ammonium perchlorate and dichromate	3400	950	3.0

TABLE 9 *Safety characteristics of four powder mixtures*

Mixture	Index of detonation sensitivity cards*	Sensitivity to friction (Newtons)	Ignition Temperature (°C)	Sensitivity to static electricity
Aluminum and ammonium perchlorate	350	171	250	very sensitive
Aluminum and potassium perchlorate, and aluminum stearate (compacted)	300	26% of ignition at 353 N	400	low sensitivity (> 726 mJ)
Zirconium and copper oxide	< 1	150	520	very sensitive (< 1 mJ)
Zirconium and barium chromate, and ammonium perchlorate and dichromate	< 1	52	280	very sensitive (3 mJ)

* Card gap test—French test, see Chapter 7.

6. Laboratory to Industrial Production: Development Programs, Service Life, Research Programs

6.1. GENERAL INFORMATION

The development of a modern weapon system, or of a space launcher, is characterized by the simultaneous and interdependent development of complex subsystems, whose production in conformance with the initially determined specifications and schedule spells the success or failure of the entire program.

In addition, the technologies involved demand, as a rule, a very high degree of development: high performance and reliability are usually the primary characteristics.

Consequently, it is necessary to reduce to a minimum contingencies and uncertainties at the beginning of the program, from a technical point of view as well as from a financial one. This implies the use of proven technologies and methods. Because the programs involved are long-term, complex, and costly programs, and because many disciplines, professional specialities, and industrial capabilities must be involved in a coordinated manner to reach the goal, special program management methods and specific organizational rules must be applied.

Under these conditions it is understood that, at the beginning of the development of the propellant grain or of the motor, the products, processes and methods to be used in the implementation of the program must be sufficiently proven.

The terms research and development are used in the solid propellant industry with a specific meaning.

The goal of the research is, generally, to develop and qualify materials, processes, and measurement processes which will be used later in the development of a motor or a propellant grain when the decision is made, by a company or by government authorities, to develop a new system.

Propellant research, for example, must go from the laboratory phase, involving several grams of the substances, to "Scale 1" at industrial facilities capable of using several tons of the product. In the case of materials used in a motor, research includes "exploratory development." At this stage, however, research is not immediately finalized. It will only be finalized through its direct application in a system.

6.1.1. Definition of the term "development" and general organization of development programs

According to the official definition, development is: "all activities with the purpose of developing devices, processes or materials responding to well-defined specifications, and which can be built or implemented in a reproducible manner".

To use more precise terms, the purpose of engineering development is:

- to design and define the propellant grain responding to a specific need;
- to justify the design through tests, and if necessary, overtests, and by simulated use;
- to establish mandatory production and control methods to ensure overall quality of future industrial production;
- to prepare the industrial documentation for future industrial production and quality control of the product;
- to determine, with the client, the conditions for acceptance of the future series production.

6.1.2. Determination of the requirements, setting of the specifications

The determination of the requirements must, however, be as detailed and exhaustive as possible; it involves:

- a detailed look at the operational requirements of the future motor;
- expressing them in specifications for the grain.

The major types of specifications are described in Chapter 2.

Frequently, the determination of these specifications will require repetitive steps. At this particular time, a joint review with the client of the impact of the various specifications on the cost and final product quality for industrial production, is of major importance. The techniques of functional or value analyses applied at this stage provide a very efficient means of achieving the optimization of cost and quality.

6.1.3. The program

The technical proposal forms the basis of the commitment of the company or organization in charge of the development.

This technical proposal includes a development program, divided into various phases. The logic of the activities planned within each phase, and the sequencing of the successive phases, have to demonstrate that the objectives of the program will be reached without major obstacles.

In France, as an example, the phases usually planned in a program are:

- development, tailoring, and manufacturing, testing to reach a final design ("MAP 1");
- qualification by the contractor ("MAP 2");

- official qualification of the grain (called certification when done by governmental action);
- the industrial phase: implementation of the industrial facilities and qualification of the production line.

The content of the program, in particular the number of tests performed, will naturally vary as a function of the complexity of the grain and the degree of innovation of the project. The length of the program will depend both on the number of tests, and on the industrial cycle of the product considered.

Purely as an example, the number of tests necessary for a grain used in a tactical application which requires to perform within a large range of temperatures can vary from 10 to 20 (in a simple case), and 30 to 40 for the development phase (MAP 1). The number of tests performed during the internal qualification or certification phase is, of course, contingent on the requirements of the client. The number of tests can also be determined by requirements related to demonstration of reliability requiring overtests (more stringent conditions) and to the performance of safety and vulnerability tests. The duration of the development may vary from 2 years in exceptional cases to approximately 4 or 5 years for tactical systems, and up to around 10 years for strategic or space systems.

6.1.4. *Role of value analysis in the clarification of the requirement during the preliminary project and the project*

This technique is designed to assist in finding the best compromise for the definition of the product in terms of its performance and its cost. Briefly described, a value analysis consists in giving responsibility to a group of individuals, having various roles in the project, who together perform a functional analysis of the product with the objective of finding a means of reducing the production cost. It is a collective effort that should, to the extent possible, include the client and the subcontractors, in order to arrive at a functional expression of the requirement, the determining factor of the product's competitiveness.

6.1.5. *Design to cost*

This is the implementation of methods designed to control recurrent industrial production costs for the product under development. This method involves:

- identifying objectives for the recurring costs right at the beginning of the development program;

- encouraging, through the inclusion of contractual incentives, the search for and selection of technical solutions for both the cost objectives and development requirements (quality, performance, schedule);
- managing the recurring costs during the development, the same as for performance, quality and schedule.

6.2. PROGRAM MANAGEMENT

The methods described above, although included within the propellant grain development, are not specific to propellants. They are, for the main part, identical for the development of a motor, a missile, even an armament system. However, with a growing number of sub-assemblies or basic operations, strict program management becomes increasingly complex, even for propellant grains.

The program director needs to rely on increasingly complicated planning and information tools.

The first activity consists in a breakdown of the program into basic tasks and the creation of detailed flow-charts, known as the "work breakdown structure" (WBS).

This allows decreasing the complexity of the project, identifying its main components, and laying down a base for budgetary, scheduling and assignments planning and control.

At the technical level, the use of relatively sophisticated planning tools (for example, GANTT diagrams and critical path methods such as PERT), offers the possibility of emphasizing the logic and the critical interfaces, and of seeing whether the planning has been realistic. It results in a better appreciation of the principal difficulties, and the possibility of analyzing fall-back solutions or alternatives.

At the program cost and budget control levels it provides the possibility of having available, in real time, information necessary to evaluate the economic performance by comparing expenses with work performed, and the remaining expenses and work.

Nowadays, software systems for program management that integrate this type of services are available commercially, and their use is becoming increasingly frequent, particularly in the space industry.

6.3. SERVICE LIFE

This is one of the most difficult questions that will face the individuals in charge of the development of a new motor or a new grain.

The client or prime contractor usually wishes to know the estimated service life or—a direct consequence—the replacement cycle of the motors.

Unfortunately, that question can only be answered with great caution at the beginning. As we will see later, it is therefore advisable to accumulate a maximum of relevant information, starting at the time of the research phase. Similarly, it is necessary to use the greatest possible amount of information that can be provided by results from the operational behavior of existing motors and grains, whose designs are as similar as possible.

During the development, although at a time when the designs are sufficiently determined (at the end of MAP 1, for example), it is possible to start what is commonly known as "accelerated aging," which will provide the opportunity of estimating the potential life at the end of the development phase. Ideally, to have the best estimate, the development phase would have to last at least as long as the projected service life, and provided that the impact of the various "treatments" the missile is subjected to when in use can never be entirely simulated, have a limited impact. The principle of these accelerated agings usually consists in using an increase in temperature to increase the rate of the chemical phenomena responsible for the evolution of the materials that make up the grain. Extreme caution is recommended, however, because the failure processes can be of different natures, and the temperature can impact differently on each of them, so that, in the worst case, it is possible to create a failure that would not occur in the real application. There have been such instances.

General recommendations in this regard are as follows:

- The temperature increases and accelerated aging must remain within modest ranges to be representative.
- The samples, subjected to aging, must be as representative as possible of the propellant that will be industrially manufactured.
- Not only non-destructive and firing tests must be performed on the aged samples, but also detailed and analytic evaluations. It is these evaluations alone that provide the capability of creating models of the evolution of the safety ratio throughout the service life, as various properties of the propellant change.

6.4. IMPORTANCE OF THE RESEARCH PHASE

We have determined that the teams responsible for the development of a new grain must have access to proven technological tools, materials and propellants, so that they may propose development programs that are short and without contingencies.

The mission of the research teams is to supply these elements, and in particular:

- create and validate methods to design the grains, estimate their service life and estimate their operation under all types of working conditions;
- formulate, identify the characteristics, and implement up to the industrial feasibility stage any new materials that are necessary for the progress of the technology and the needs of the development.

Industrial considerations should be present very early during the research. As much as possible they should be the principal factor in major decisions concerning the various possible routes to reach the objectives selected for density, specific impulse, burning rate, etc. This is particularly true for the considerations of process costs and of raw material availability.

The last point is of particular importance for the continuity of the industrial production, which in some cases can last for over 20 years, and for systems which, when they are modified, require new certifications which are extensive and expensive because of the interaction between the sub-assemblies. The company supplying the propellant is rarely the manufacturer of all, or even most, of the raw materials included in his products. The company is, as a result, totally dependent on the industrial and commercial strategy of its suppliers, or on official authorizations for imported products. It is therefore advisable to ensure that the raw materials selected have solid long-term guarantees, and to undertake, at the beginning of the research, actions such as surveying substitute products, certifying second sources, preparing supply agreements and so forth.

It is also necessary, when developing a new propellant, to test a sufficient number of samples of those raw materials that have the greatest impact on the quality of the propellant, to determine reproducibility and to have control capabilities at a later time. Of course, these activities must be completed during the development *per se*. Specific technical adjustment must be made during the development phase, although the assessment of particular propellants or materials for a new development must use this raw material information base as much as possible.

Finally, it will be necessary to have, already at this stage, as much information as possible concerning the aging of the propellant and related materials under conditions similar to the future conditions of usage. This requires that very early, during the research phase, programs be initiated to learn about the mechanisms of degradation and the laws of evolution of the products over time.

Based on the service life required for today's propulsion systems, and the limitations of accelerated aging methods in standard environmental conditions, it is unfortunately rather rare to have a thorough knowledge of those characteristics at the onset of the development of a grain. It is true that, for older materials, their service life characteristics are well known, but these materials do not have the performance characteristics now required. To gain a better appreciation of grain life it is necessary to:

- strengthen the initial selection by using as much aging data as possible, gathered from similar products under research, or from older grains with practical experience that has been accumulated through monitoring programs;
- perform, during the development phase, the evaluation programs described previously.

This discussion emphasizes the importance of the role of the development activity for the orientation of the research, and the inclusion of the research within a broader perspective, which can be considered as being particular to this type of industry.

6.5 ADVANCED DEVELOPMENTS AND EXPLORATORY DEVELOPMENT MODELS

When very advanced technology is involved, an exploratory phase is often included between the research phase and the development phase. Its purpose is to confirm, at "Scale 1," that the right combination has been made of design method equivalents, processes, and materials in a new type of propellant. This advanced development can be considered as the furthest culmination of the research, and the surest way of having a shorter development phase (because of the reduction of the number of tests required) without any unpleasant surprises.

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