Overview of pyrotechnic components and technologies for space launchers

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Abstract
At take-off and in flight, space launchers require specific systems to achieve the following functions: ignition, separation, passivation, deorbitation, delay and destruction.
Since the 60's, electro-pyrotechnical systems have been implemented on most of launchers throughout the world and have proved their efficiency. The current components installed on launchers for end functions exhibit proven reliability and availability. Nevertheless, every time a new launcher is in development, the choice of the pyrotechnic system arises, which relies on a complex balance between performance, safety, cost, reliability, availability, and ease of integration process. This paper proposes first an overview of the Ariane 5 ECA pyrotechnic heritage and then introduces future pyrotechnic systems in order to contribute to the pyrotechnic system choices for new launchers.

1. Introduction

Space launchers require specific pyrotechnic chains to achieve several functions described on **Figure 1**. On Ariane 5, the first function is engine ignition: Vulcain on the main cryogenic stage (EPC) and HM7 on upper cryogenic stage (ESC) for liquid propulsion, solid rocket motors (SRM/EAP) for solid propulsion. During the mission sequence, SRM's are first separated and distanced from the main core. Then, the fairing is opened and jettisoned. The last operation consists in the upper stage separation from the main cryogenic stage. In case of launcher dysfunction with a safety impact, the pyrotechnic self-destruction system is triggered.

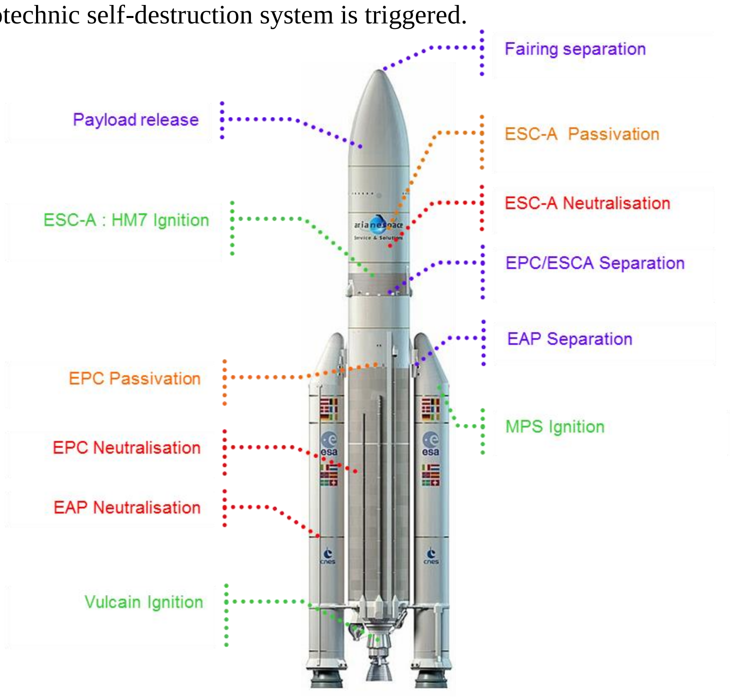

Figure 1. Pyrotechnic functions

A new launcher constitutes an opportunity to examine new technologies whose selection has to be carried out taking into account lessons learnt. This selection has to include safety concerns, cost constraints, reliability, integration and tests issues. This paper proposes to remind first the heritage of Ariane 5 pyrotechnics under the aspects of safety, reliability, then to present how external constraints and technologies have pushed forward innovation and R&T programs.

2. European Space pyrotechnics: more than 30 years of experience

2.1 Pyrotechnic chain on launchers

Pyrotechnic devices are implemented on space launchers in order to achieve several major mission duties. The success of these different functions relies on the pyrotechnic chain, repeated on the whole launcher and detailed on Figure **2**.

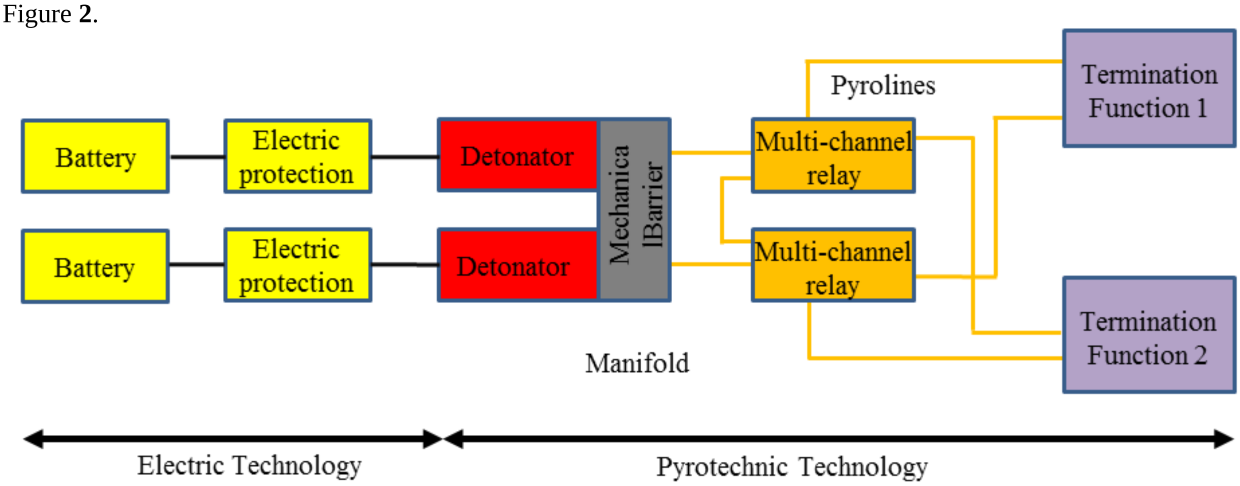

Figure 2. Pyrotechnic chain

From left to right, the batteries provide power to detonator which is prevented from inadvertent ignition by electric barriers. The mechanical safe and arm device (SAD) independently actuated by ground safety, protects the pyrotechnic chain and the launcher from a catastrophic event. The detonator ignition starts the detonation propagation through pyrolines. The pyrotechnic signal is self-sustained within the pyrolines where multi-channel relays distribute the signal and ensure re-synchronization. If necessary, time delays are implemented on the pyrotechnic chain, from 5 to 25s on Ariane 5. Eventually, the signal reaches the terminal function to achieve the required function. The

Table 1 details several pyrotechnic devices implemented on European launchers for more than 30 years [1].

Table 1. Pyrotechnic devices history

Device	Origin year	Qualification year	Launcher (s)	Evolution
Detonator/squib	1969	1977-1988	Ariane 4 – Ariane 5, Vega	Adaptation from Ariane 4 to Ariane 5
Safe and Arm Device (e.g. BSA)	1987	1993	Ariane 5, Vega	No major evolution
Pyroline	1976	1977/1983	Ariane 4, Ariane 5, Vega	Two pyrolines with one hardened version
Pyro delay	1977	1978	Ariane 4, Ariane 5, Vega	No major evolution
TEE (HSS, SSS…)	1983	1987	Ariane 4, Ariane 5	Design evolution to reduce shocks
Cutting cord	1967	1968-1969	Ariane 1-5, Vega	No major evolution
Ariane 4/Vega pyro manifold (BMU)	1978	1987	Ariane 4, Vega	Increase of pyrotechnic channels
Ariane 5 multi-	1990	1995	Ariane 5	No major evolution

Device	Origin year	Qualification year	Launcher (s)	Evolution
channel relay(RMV)				
TBI (IFOC)	1981	1984	Ariane 5, Vega	Vega evolution
Liquid propulsion igniter	1974	1979/1987	Ariane 4, Ariane 5	Viking, HM7, Vulcain
Liquid propulsion starter	1974	1977	Ariane 4, Ariane 5	Viking,HM7, Vulcain
Vertical Separation system	1974	1978	Ariane 4, Ariane 5, Vega	No major evolution

All these devices have required some modifications from their qualification and acceptance tests up to now. Usually, evolutions are implemented step by step in order to reduce development risks and not to disturb the correct functioning of mounted devices on launchers.

2.2 Pyrotechnic safety

By nature, pyrotechnic functions may lead to catastrophic events and safety is a main issue to manage all over the life cycle.
Two ways have been adopted to ensure the safety linked to pyrotechnics items:

- Regulations
- Safety tests in order to characterize pyrotechnics equipment.

The launch base safety is managed by further regulations and good practices, in the particular case of the pyrotechnics items:

- French Space Operations Act (FSOA), including:
    - Decree regulating the operation of the Guiana space center facilities (CSG)
    - Decree concerning technical regulation
- Former decree on pyrotechnics, now included in the French labor law.
- Good practices defined by the GTPS – Groupe de Travail Pyrotechnie Spatiale: Working group composed by further actors of the French pyrotechnics industry.

The main safety rules applied in the CSG are provided by these regulations. Hereafter, a focus is made on the main rules which have a direct impact on the pyrotechnic chains, architecture and subsystems, or an impact on the control process, integration process or any activities during ground operations:

- A safety submission process is implemented for each hazardous component, sub-system, system in order to assure safety on ground and in flight.
- 3 safety barriers have to be implemented when a catastrophic risk can occur (i.e. Immediate or delayed loss of human life, permanent invalidity, Irreversible harm to public health)
- The electro-explosive initiators (squib, primer/detonator) must provide a level of safety at least equivalent to those of type 1 A, 1 W, 5 mn non-firing.
- The electrical circuits of the pyrotechnic systems are designed so as to limit the induced currents on the firing circuit to at least 20 dB below the maximum non-firing current.
- The installation of electro-detonators and/or connection of hazardous classified electro-explosive systems must take place as late as possible in the launcher or payload preparation sequence.
- For pyrotechnic systems entailing a risk of catastrophic consequences, the closest barrier to the hazardous source must be mechanical (the safe and arm device) in order to prevent inadvertent firing of the system.

In addition to these regulations, an important effort in order to characterize pyrotechnic equipment and chains has been performed particularly to determine the sensitivity to different aggressions that pyrotechnic components and chains could be subjected to in the environment of the launcher.
The tests performed have allowed a better knowledge of the pyrotechnic equipment and chains and of their behavior in the following degraded contexts:

- Thermal aggression:
    - Slow cook off: date the initiation of pyrotechnics equipment during a weak fire
    - Fast cook off: date the initiation of pyrotechnics equipment during an important fire
- Mechanical aggression:

  - Falls: Determine the sensitivity (integrity, spurious functioning) of pyrotechnics equipment (especially detonators) when a fall occurs. Tests have been performed at two different heights: 2m (equivalent to man height) and 12m (equivalent to platform height).
  - Sensitivity to collisions of a cutting cord: determine the sensitivity of a cutting cord (spurious functioning) when it is submitted to mechanical impacts.
  - Fall of a distancing rocket: Determine the consequences of the fall of a distancing rocket on its ignition head.
- Electrical aggression:
  - Susceptibility to electrostatic discharge: Verify the non-susceptibility of pyrotechnic equipment when it is submitted to an electrostatic discharge (no spurious functioning).
- Lightning aggression:
  - Verify the absence of spurious ignition of pyrotechnic equipment and chains when submitted to lightning.

Thanks to these tests, the safety sheets of each pyrotechnics component have been updated with the specific degraded environment possibly encountered during a launch.
These tests have allowed a better knowledge of the technology and of its limits.

Beyond regulations and tests, pyrotechnic architecture is also based on the lessons learnt of accidents.
Feedbacks of accidents are taken into account. For example, the lessons learned of the VLS (Veiculo Lançador de Satelittes) accident that occured in Alcantara in August 2003 have been treated in 2010 [2]. This example highlights the importance of placing a mechanical safety barrier after the initiator and more widely on the importance to refer to the former accidents when a new technology is developed.

2.3. Pyrotechnics: how to ensure reliability?

Reliability in development

During the development of pyrotechnic equipment, quantitative reliability is estimated by the use of different rules shared by the actors of the pyrotechnic domain.
This assessment is based on further statistical tests as Bruceton tests and severe tests.
Bruceton tests
The Bruceton method provides statistical estimators for mean and standard deviation, with good precision for the mean. It is a sequential approach which allows to evaluate the estimators of the mean and standard deviation of the probability distribution of functional thresholds, for a given confidence level. It uses a sequence of tests where the stress level applied at each step is a function of the results obtained in the previous step.
Severe tests
This method is suitable to confirm functional margins with respect to the nominal operating point, with less than 10 trials. It is used to validate compliance with a reliability objective for a limited number of tests of a one-shot device.
It is applicable to pyrotechnic products in particular.
In order to assess a specific reliability objective, the principle of the method is to determine a severity coefficient to be applied to the predominant functional parameter of a pyrotechnic device and to demonstrate that this device will operate "without failure" via tests at the level of severity. Reliability is also ensured by the compliance to specific design rules, implemented and known by all actors of Ariane programme and which take into account the launcher specificities.

Reliability during operational phases
Pyrotechnic items are not testable and the quantitative reliability estimated during the development phases is not verifiable during the operational phases. This is why qualitative reliability is very important for those types of equipment. Thus the reliability of pyrotechnic equipment is mainly linked to the reproducibility of the production process and to the good ageing of the materials.
In order to verify reliability during all the phases of the product life cycle, tests campaigns named LEAP (Launcher Exploitation Accompaniment Programme) are performed. LEAP is a support to Ariane 5 technologies in general, but some tests are dedicated to pyrotechnic issues.
It is based on sampling and ageing. During the production phase, a sample of produced equipment is tested in ambient and severe environment, such as temperature.
The component ageing is also characterized: they are ignited after 3, 5 and 7 years of storage (natural ageing). These tests allow verifying the reliability of the products. LEAP campaigns are very important for the pyrotechnic components reliability, as the control of the production processes. The reliability is also linked to the human skills involved.

All modifications which can impact the production process are identified and followed at all levels of the contractual chain through a critical item list (e.g. change of a test bench). Production events are recorded and a strong monitoring is performed.
Until today, no Ariane 5 launch failure has been caused by pyrotechnic equipment dysfunction.

3. Focus on Ariane 5 pyrotechnic feedback

3.1 Introduction

Pyrotechnics is a conservative field as most design changes would imply safety concerns. Nevertheless, several reasons can be identified as innovation sources: obsolescence and toxicological questions, anomalies and new technologies. Innovation is usually dedicated to reduce cost or mass, or to improve safety.
The Ariane 5 industrial ecosystem and reliability is monitored at different steps [3]: prior to integration when production issues occur on devices, directly on the launcher when devices fly out of scope of their qualification state, and a long term modification program to foresee design changes on industrial request.
We propose to study two indicators by focusing on pyrotechnic devices: **waivers, and modification proposals**. These two indicators describe well obsolescence and anomaly issues. These results focus only on pyrotechnic devices, the SRM igniter and propellant are not included in the scope.

3.2 Waivers

A waiver is issued when a device is implemented on a launcher and presents a deviation with the qualification configuration or manufacturing files. The considered data do not include the development waivers and focus on the last 5 years of exploitation. The Figure 3 describes the waivers evolution and launches per year.

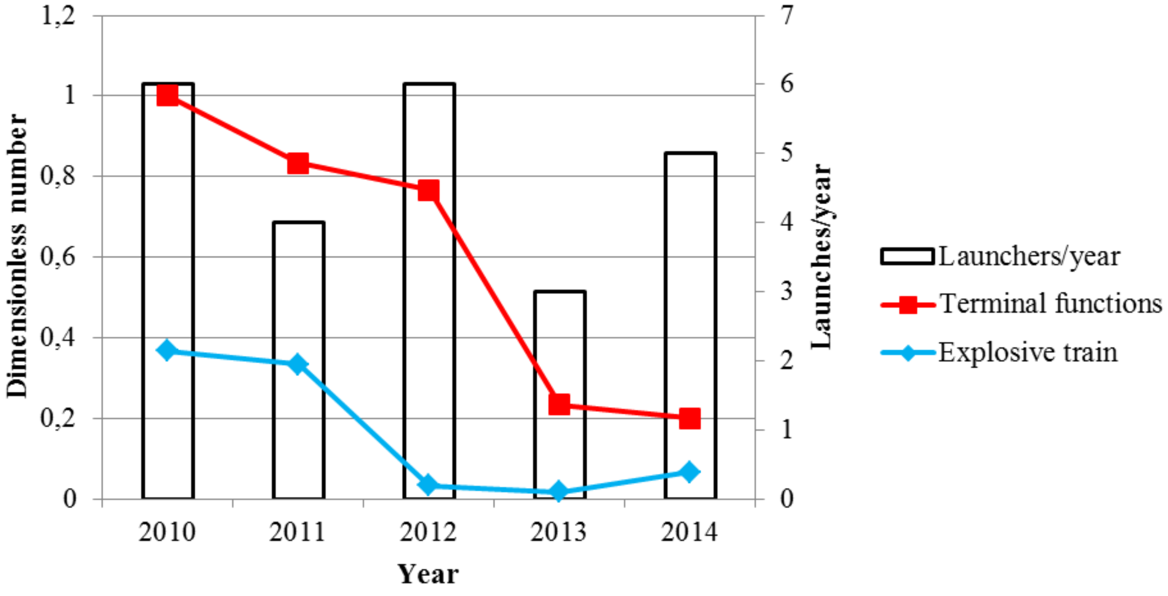

Figure 3. Waivers evolution per year

From 2010 until today, we observe a decrease in the number of waivers which can be explained by the technology maturity within the Ariane 5 ECA launcher and a better control of components production processes.

3.3 Modification proposals

Modifications proposals dealing with pyrotechnics have been implemented on A5ECA launcher since its beginning in 2006. These modifications are proposed by the manufacturers in order to improve their system or when they are faced with obsolescence. The technical field considered is detailed on Figure 4, and the evolution is shown on Figure 5.

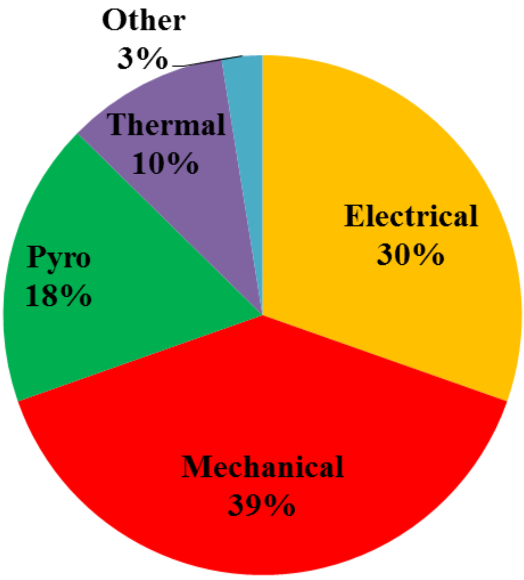

Figure 4. Technical types of modification proposals

The modification proposals types are presented on a pie chart in Figure 4. The pyrotechnic modification proposals from 2006 to 2014 have been divided into several technical categories: mechanical, electrical, thermal, and pyrotechnic and others.
The mechanical modifications deal with several points: tightness and seals, tightening torque, material, and surface treatment. The electrical modifications include the following issues: ground-board interfaces, mechanical barrier electrical interface, electrical tests on devices, connectors. Modifications proposals focused on pyrotechnics are linked with acceptance tests, storage, obsolescence and energetic materials. The thermal modifications mainly concern thermal insulation and protections, but also heaters implemented on several components.

The figures show that the pyrotechnic materials only account for 18% out of the modifications on pyrotechnic components, compared to mechanical or electrical modifications. The first explanation is accessibility: the explosive is enclosed whereas mechanical parts are directly modifiable. Globally, modifications on explosives involve important issues on qualification, acceptance tests and pyrotechnic interfaces. At mechanical level, the modifications are easier to implement and less hazardous. The modifications on explosives are often made only for compulsory cases which explain their low amount.
The Figure 5 shows the evolution in the number of modification proposals between 2006 and 2014 for the terminal functions and for the pyrotechnic chain.

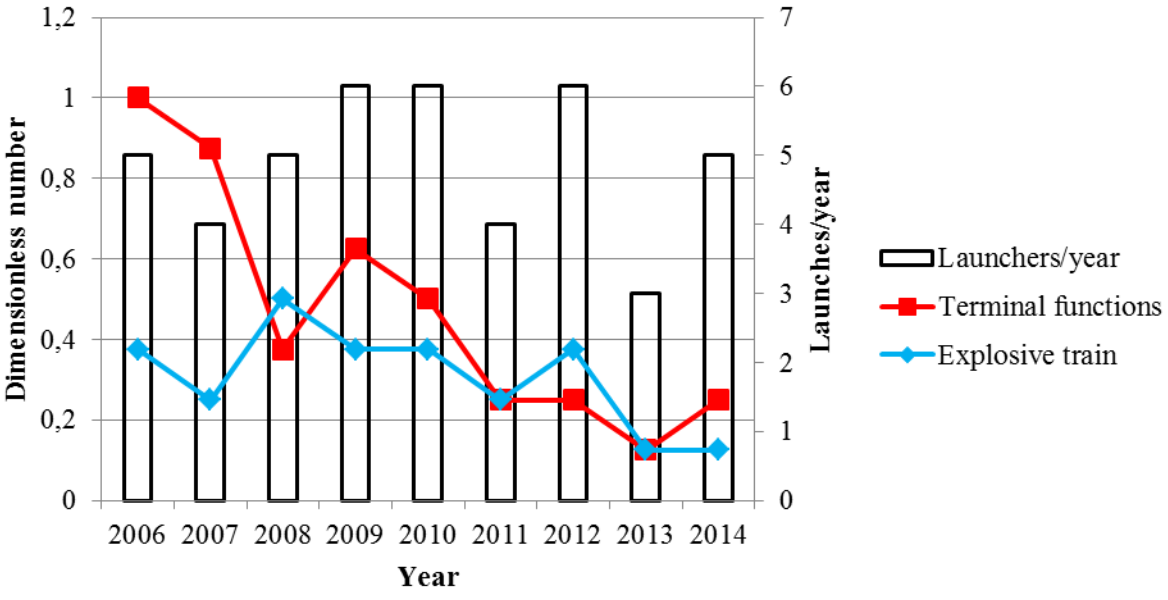

Figure 5. Modification proposals evolution

A continuous decrease is observed on modification proposals. The explanation for the initial high number of modification proposals comes from the numerous modifications proposed after the launcher failures which occurred in 2002 and 2003. The explanation for the decrease comes not only from the technological maturity but also from increases in the maturity of integration processes.

3.4 An example of Ariane 5 pyrotechnic enhancement

On Ariane 5, stages are separated by cutting the circumferential structures thanks to pyrotechnic systems. This cutting concept relies on an oblong detonating cord which is initially mechanically constrained. Detonation travelling inside the detonating cord implies an expansion of the detonating cord. This expansion creates a shear within the structure to be cut.
The initial cutting concept included a simple branch to be sheared [4]. This configuration generates shocks due not only to the pyrotechnic shock but also due to the sudden release of mechanical constraints. In order to reduce induced shocks, especially at payload level, different solutions were envisaged.

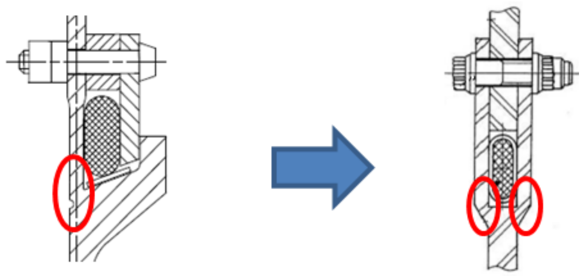

Figure 6. Configuration change for fairing separation system [4][5]

The preferred solution has been a double branch structure (Figure 6), which enables to reduce shocks propagation. Indeed, adding a branch divides the shock propagation into two waves. The shock waves junction implies a compensation which attenuates the shock level. This modification is a typical example of pyrotechnic systems improvement.

3.5 Conclusion on Ariane 5 feedback

The different processes implemented to track modifications and qualification deviations have shown their efficiency. Indeed, the absence of major failure reported on pyrotechnic systems, in addition to redundancy, enables to prove the

robustness of the current Ariane 5 pyrotechnic architecture. The continuous decrease of modification proposals and waivers has demonstrated that Ariane 5 pyrotechnic components have reached a satisfying maturity.
The pyrotechnic technology is complex because the pyrotechnic devices are at a crossroad between electrical, mechanical, chemical and pyrotechnic fields. Moreover, the whole chain is interfaced with ground operations and human risk mitigation at every step of launcher integration. This complexity is the reason why Ariane 5 pyrotechnic production still requires monitoring and justifies the tracking processes.

4. New technologies on new launchers

The current chain is mature but this technology is faced with different constraints:
- Health regulations, REACH requirements and other regulations
- Cost reduction,
- Mass improvement,
- Obsolescence risks reduction: neutron imaging…

As a consequence, space industry has to investigate new technologies going from simple improvements on existing technology to disruptive innovations.

4.1 Pyrotechnic chain

Disruptive technologies
The pyrotechnic chain has been the topic of several national research and technology (R&T) programs for years. The content of the R&T has usually focused on disruptive innovations. For more than 15 years, CNES R&T has dealt with two disruptive technologies:

- Optopyrotechnic technology
- Digital pyrotechnics

The current pyrotechnic chain technology transmits at the same time information which is the pyrotechnic signal, and the energy to achieve the information. The studied innovative technologies were inspired by information transmission technologies: optical fibers and digital busses.
On the first hand, the optopyro technology was implemented on Demeter satellite (1998-2004) under CNES Satellite R&T support [4] and these studies were coupled to CNES Launcher R&T until 2008 in order to investigate advantages and drawbacks of this application on a launcher [7]. On the second hand, digital pyrotechnics have been investigated for launcher CNES R&T since 2011 [8]. These two technologies, optical fiber and digital bus, present common points:

- New technology introduction for disruptive innovation
- Pyrolines removal and direct connection between the detonator and the terminal function
- Data transfer technology
- Testability

These new concepts are typical of external technologies which enrich the pyrotechnic field. Publications on optopyrotechnic topic have been already released in conferences on pyrotechnics since 80’s until now [9][10] following the laser technology widespread development. More recently, idea of using digital bus on pyrotechnic system has appeared since early 2000’s [11] until now [8] in association with nanothermites technology [12].
These two kinds of innovation are more likely to be settled on a new launcher where thorough modifications are allowed. Indeed, changing the pyrotechnic chain technology involves impacts which could not be implemented on an existing launcher:

- Ground/ board interfaces
- Electrical power budget
- Explosive interfaces demonstration
- Reliability demonstration
- Safety demonstration
- Integration and test logic

These two disruptive technologies would have to prove their efficiency and resulting enhancements compared to electropyrotechnic technology in terms of recurring cost and especially safety in order to be installed on a new launcher.

Improvement of the concept
The pyrotechnic chain has been originally used for mining and has been reinforced for launcher and military applications. Therefore, numerous technologies exist which do not modify the overall concept: flexible shock tubes

and flame propagating transfer lines. In these cases, the reaction speed is 4 to 6 times lower but the recurring cost is also lower. Nevertheless, strong effort would be required on development in order to reach the same level of reliability and robustness.
Otherwise, for toxicological and environmental reasons, lead could be impacted by REACH regulation. If REACH regulation includes lead as a forbidden compound in the future, the lead coating the transmission detonating cords produced for Ariane 5 may be replaced. Several metals are candidates for this replacement: aluminum, tin, silver...
This modification requires a specific development but would not constitute a technological obstacle.

4.2 Terminal functions

Disruptive technologies

Pyrotechnic terminal functions are dedicated to ignite propellants, cut materials, or distance stages. The currently implemented technologies are a heritage from past.
For ignition of liquid propellants, many solutions exist like laser, capacitive discharge and sometimes use intermediate hot gas premix tube [13][14]. We also find pyrophoric compositions on Falcon launcher [15]. All these solutions are strongly dependent on the engine cycle but also on the system and cost constraints. Some of these technologies are not properly disruptive but their adaptation to the Ariane launcher would be.
For ignition of solid propellants, the Through Bulkhead Initiator principle remains the simplest compromise between chain safety and detonation transmission, tightness requirement, and ignition requirements.
For separation concepts, innovative technologies on launchers would be mainly inspired by satellites technologies [16]. The separation technologies share the need to reduce separation shock, which is due not only to the tube pyrotechnic expansion, but also to the sudden release of mechanical constraints. On satellites, the Non Explosive Actuators are common and replace pyrotechnic devices: hold and release systems, shape memory alloy systems, piezoelectric systems, etc.[17]. The main issue regarding these technologies is the drastic increase of the level of mechanical constraints from a satellite configuration to a launcher configuration. The temperature domains and response times, for shape memory alloys, also constitute issues for implementation on a launcher.
The pyrotechnic distancing systems mainly consist in rockets and pyrojacks. The replacement solutions like springs depend, as for satellite separation systems, on the mass to be distanced.
For neutralization systems, which require cutting liquid propellant tanks or solid propellant casing, there is currently no available alternative technology.

For terminal functions, several situations of evolutions can occur, depending on the goal of the function:
- For liquid propellant ignition, alternative technologies exist and could be implemented
- For solid propellant ignition, there is no credible alternative
- For separation and distancing functions, alternative technologies exist. Their current technical characteristics are not compatible with the launcher constraints. Nevertheless, important improvements could be performed in the future.
- For neutralization systems, there is no credible alternative.

Thus, up to now, innovation to fulfill terminal functions objectives have been usually limited to existing system improvements.

Improvement of concept: The example of Linear Cutting charges

Linear Cutting charges are implemented on launchers in order to ensure its self-destruction in case of major malfunction during the flight. Their production life from the beginning of Ariane 5 ECA has required improvements and modifications in order to ensure reliability.
Several years ago, the production was faced with obsolescence on the manufacturing bench. The time to recover the same level of knowledge and know-how on the brand new bench implied performance fluctuations. These fluctuations were tracked at different levels during their production life.
On 2007, Meyer-Lassalle and Rondot [18] published both numerical and experimental results in order to understand why the performance decreased for 17x17 mm LCC. As we can observe on Figure 7, a double channel (on the left) occurred on the aluminum plate for suspicious when a single line is expected (on the right).

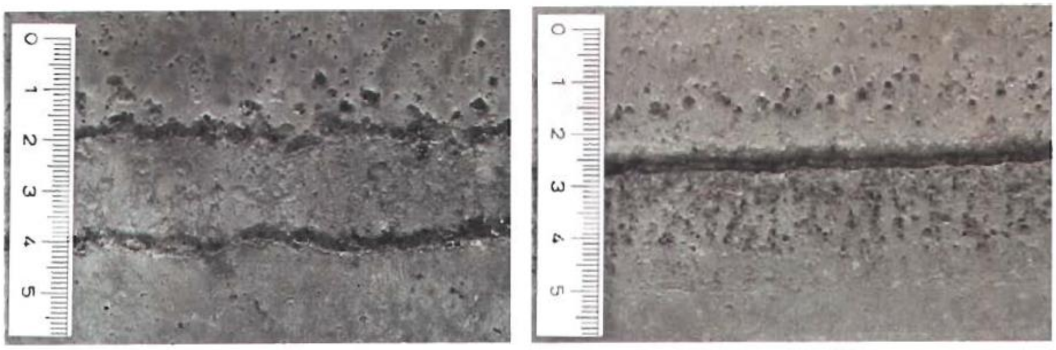

Figure 7. Penetration target on aluminium plate with suspicious and standard lead cutting cord [18]

This study funded by CNES R&T aimed to compare X-ray pictures, penetration performance and numerical results for standard and suspicious batches. The obtained picture and numerical simulations are shown in Figure **8**. The LCC curvature has been identified as the main cause. This study has helped to improve production performance stability on short-term.

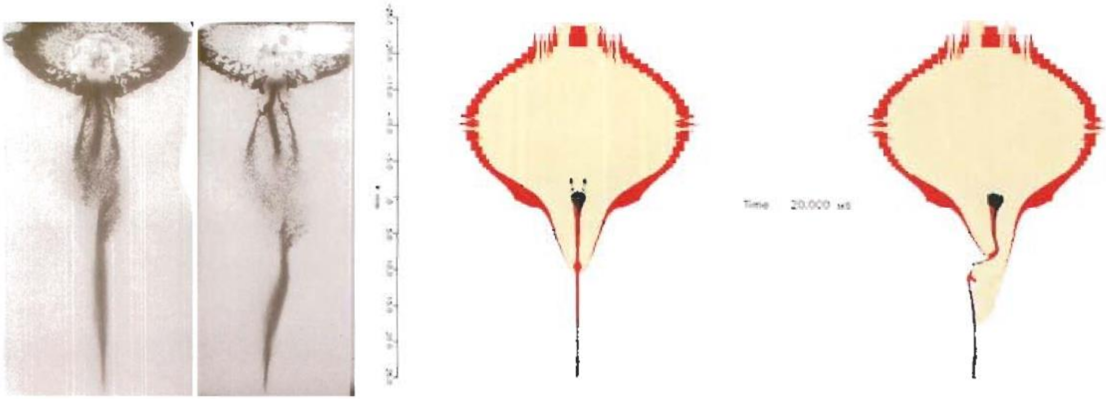

Figure 8. Comparison between X-ray imaging and numerical simulation for suspicious detonating cords [18]

As a consequence, on a long-term framework, a second study has been initiated between CNES and Pyroalliance in order to create a new LCC without lead for toxicity reasons. As the manufacturing process had been identified as the major cause of qualification waiver, a strong effort has been performed on this aspect.

Thus, a new manufacturing process has been developed in order to fulfil requirements in terms of cost, performance, and reliability and production stability. Contrary to the current lead-based LCC requiring a continuous process, this process allows separate controls and tests at different steps of manufacturing: envelope integrity, explosive loading...

As a result, the first penetration results of this study have been published in [19] and exhibit promising preliminary results. Indeed, at equivalent cutting cord size configuration, penetration performance is increased by 50%.

The Figure 9 shows a penetration picture on mild target where the channel exhibits a clear and homogeneous penetration. Numerical simulations have been performed and fit well with the observed hydrodynamic expansion thanks to X-Ray imaging performed at ISL.

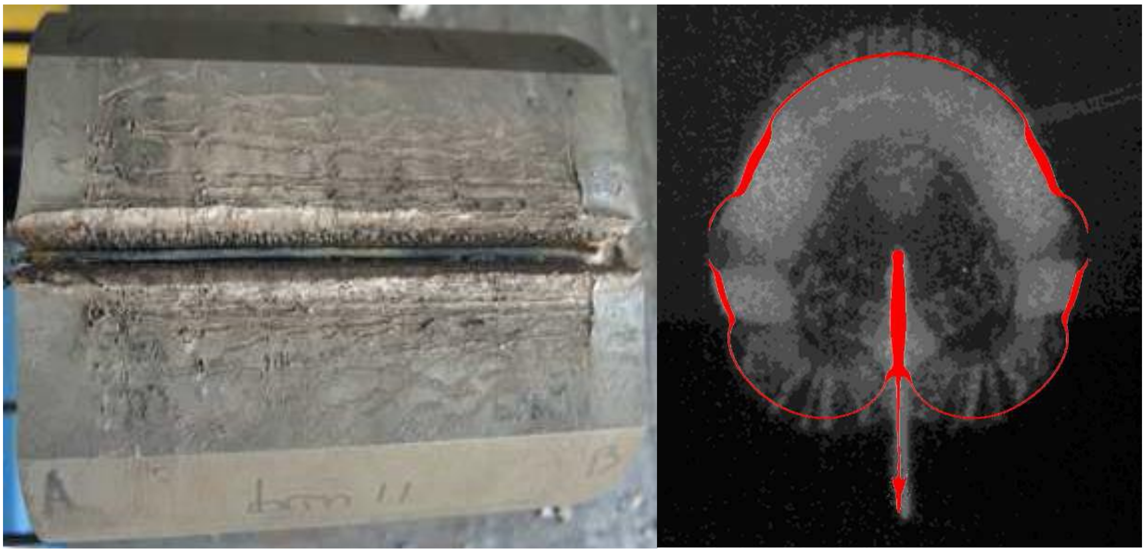

Figure 9. Penetration of RDX/Copper Linear cutting cords (left) and superposition of flash X-Ray and numerical simulation of cutting cord expansion (right) [19]

These preliminary results constitute a good example of a production issue leading to innovation and performance improvement.

4.3 Neutron imaging example: a constraint turned into innovation?

The current pyrotechnic chain and some terminal functions are inspected thanks to neutron imaging. These nondestructive tests enable to track heterogeneities and pollutions in the explosive. In the mid-term, the test bench is faced with an obsolescence issue. Different solutions exist to replace this test set-up. The first one is to change the metal coating of pyrolines (made of lead currently) in order to perform X-ray visualization. Several metals can be candidates: aluminum, tin, silver... The second solution is to directly use other nondestructive visualization technologies: tomography, ultrasonic inspection. A third solution could be to implement a complete disruptive pyrotechnic chain (cf. §4.1) but terminal functions control would not be solved.
Thus, a unique replacement solution is hard to find and will require a strong technical effort and investment. This is a typical example when an obsolescence issue can imply different kinds of innovation.

5. Conclusion

Pyrotechnic products used in the Ariane 5 launcher have been tested and improved for years. Their processes have been optimized through the creation and the implementation of design rules. Now we can say that the production and integration processes are well managed. Products are well known and characterized. Some anomalies still occur, but their number is decreasing. Today they are mainly due to obsolescence, change of production means or regulations constraints.
Indeed, new regulations such as REACH and the obsolescence require changes and innovations for the current products. These changes can lead to the improvement of the existing products or the development of a total disruptive technology.
We observe that the improvement is usually preferred for terminal functions, where a huge energy is required within a short time to ignite, propel or cut structures. Pyrotechnics remain the most appropriate technology to achieve these functions.
On pyrotechnic chain, the past and current R&T studies have privileged disruptive technologies. The current chain fulfills pyrotechnic and transmission functions. The transmission is not specific to the pyrotechnic chain and can be performed by other technologies like the optical fibers or the digital bus. The main issues remain safety and the interfaces between the chain technology and the terminal function technology.
As a conclusion, for disruptive or improvement cases, the heritage of the current Ariane 5 pyrotechnic should be taken into account for future launchers:

- Severe safety tests and severe environments have to be performed on future technologies
- The current tracking and accompaniment system of production events, modification proposals, waivers and also LEAP sampling and ageing has to be conserved in the future for pyrotechnic devices.

- For disruptive technologies, the test logic would require robust safety and reliability assessments.
- During technology development, comfortable performance margins would be required to tolerate interfaces and system deviations from the original specification

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